# INFLUENCE OF SPONTANEOUSLY GENERATED COHERENCE AND RELATED PHASE ON AN ALL-OPTICAL SWITCHING IN A THREE-LEVEL LADDER-TYPE SYSTEM WITH INCOHERENT PUMPING

**Luong Thi Yen Nga[1], Nguyen Huy Bang[1], Le Thi Dung[1], Hoang Minh Dong[2], Trang Huynh Dang Khoa[2], Nguyen Thi Thu Hien[1, 2,*]**
[1]*Vinh University, Vietnam*
[2]*Ho Chi Minh City University of Industry and Trade, Vietnam*

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****Correspondence:***
*hien0ntt@gmail.com*
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**ABSTRACT**

This paper investigates the impact of spontaneously generated coherence (SGC) and relative phase on the propagation of a probe laser pulse in the presence of an incoherent pump field. It was discovered that when the control laser field is turned on, the medium forms an electromagnetically induced transparency (EIT) effect. Hence, the propagation of the probe laser pulse has a like-soliton form/shape. On the contrary, the probe laser field is rapidly attenuated when the control laser field is turned off. This feature allows the creation of a mechanism to turn "off" and "on" the probe laser field through "turning off" and "on" the control laser field, i.e., an all-optical switching mechanism based on EIT. Besides intensity and frequency, the laser field is also characterized by polarization and phase. The EIT has the nature of quantum interference, so it is very sensitive to changes in polarization, especially in the presence of relative phase between laser fields. Therefore, they also significantly affect pulse propagation and optical switching performance. The research results could be helpful for experimental observations or applications in photonic devices such as logic gates, quantum optical information processors, and quantum computers.

**Keywords:** All-optical switching; EIT medium; quantum interference; three-level ladder system.

## 1. Introduction

All-optical switching is an essential component in high-speed optical information networks and has potential applications in quantum information systems [1]. Over the past decade, ultrafast all-optical switching has been a topic of interest for many researchers, and there have been many groundbreaking proposals to improve the speed and performance of all-optical switching. In particular, all-optical switches use electromagnetically induced transparency (EIT) [2], electromagnetically induced grating (EIG) [3], etc. All-optical switching based on quantum interference has outstanding advantages, such as high responsible speed and low switching power compared to electro-optical switching and silicon waveguides or fiber-based systems [4-6, 8].

Besides the EIT effect, another quantum interference effect arises due to the superposition of spontaneous emissions within a multilevel atomic system combined with the non-orthogonal orientation of displaced dipole moments, producing spontaneous emission of atomic coherence called the spontaneously generated coherence (SGC) effect. Theoretical and experimental studies show that when the EIT and SGC effects are present simultaneously, SGC does not damage the EIT effect. However, it can increase the depth and reduce the transparent spectral domain, which increases the height and slope of the dispersion curve in the EIT spectral domain [9-11]. On the other hand, to increase the magnitude of the atomic coherence produced by spontaneous emission, a non-coherent pumping field is often used to increase the density of atoms in the excited state. The role of the incoherent pumping field on the atomic optical properties has also been shown in Ref. [12]. In addition, the presence of SGC also makes the optical properties of the medium very sensitive to the relative phase of the applied laser fields [12-13]. Therefore, the optical phenomena also change significantly in the presence of the relative phase of the laser fields [14].

In the pulse propagation dynamic regime, the SGC can provoke pulse modulation. However, one can use the relative phase and incoherent pump field appropriately, and these modulations can be reduced or eliminated [14]. However, in Ref. [15], the simultaneous influence of SGC and non-coherent pumping in the presence of relative phase on all-optical switching in a three-level atomic system with ladder configuration has not been considered. Following this line of interest, we propose to use a three-level atomic model with a ladder configuration to study the influence of SGC on all-optical switching in the presence of the relative phase and with the support of an incoherent pump field. By simultaneously numerically solving the Maxwell-Bloch coupling equations for atoms and fields on a space-time grid, the switching of the probe field through the control parameters of the system will be investigated.

## 2. Theoretical model and basic equations

A three-level ladder-type $^{87}$Rb atomic system, as shown in Figure 1, was considered. In this model, a weak probe laser field with carrier frequency $\omega_p$ is applied to the transition $|1\rangle \leftrightarrow |2\rangle$, while the transition $|2\rangle \leftrightarrow |3\rangle$ is controlled by a strong coupling field with carrier frequency $\omega_c$. Assuming that each field only affects one displacement, the probe laser field (or coupling laser field) will be chosen perpendicular to the electric dipole moment $\vec{\mu}_{23}$(or $\vec{\mu}_{12}$). $\Gamma_2$ and $\Gamma_1$ are given to indicate the decay rates of the states $|3\rangle$ and $|2\rangle$, respectively. The incoherent pumping field has a pump rate of 2R set between the levels $|1\rangle$ and $|3\rangle$. The Rabi frequencies of the probe laser field and coupling laser field are defined as $\Omega_1 = 2\vec{\mu}_{12} \cdot \vec{E}_p / \hbar$, and $\Omega_2 = 2\vec{\mu}_{23} \cdot \vec{E}_c / \hbar$, respectively. Set $\Omega_1 = \Omega_p \exp\left(i\phi_p\right)$ and $\Omega_2 = \Omega_c \exp\left(i\phi_c\right)$ to determine the phase $\phi_p$ and $\phi_c$ of two laser fields, with $\Omega_p$ and $\Omega_c$ as real parameters.

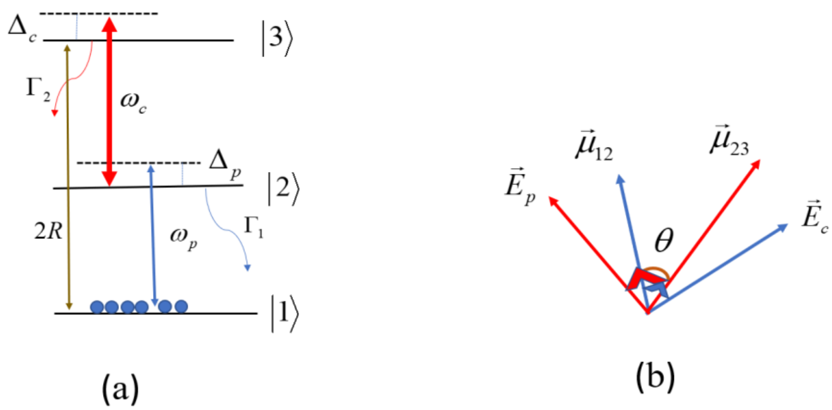



**Figure 1:** (a) *The three-level ladder-type atomic system has energy levels evenly spaced and close together; (b) The diagram of the polarization vector and the corresponding laser field is fixed so that each laser affects only one transition*

Applying the rotating wave approximation and the electric dipole approximation, the density matrix equation system is briefly presented through the expressions as follows [7]:

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

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

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

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

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

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

where, the elements of the matrix obey the conjugation and normalization conditions $\rho_{11} + \rho_{22} + \rho_{33} = 1$ and $\rho_{ij} = \rho_{ij}^*(i \neq j)$. Here, $\Delta_p = \omega_p - \omega_{21}$ and $\Delta_c = \omega_c - \omega_{32}$ are the frequency detuning of the probe laser field and coupling laser field with the corresponding atomic transitions, respectively. The term $2p\sqrt{\Gamma_1\Gamma_2}\eta\rho_{23}$ exhibits the result of cross-coupling between spontaneous emission channels $|1\rangle \leftrightarrow |2\rangle$ and $|2\rangle \leftrightarrow |3\rangle$, $p = \vec{\mu}_{12} \cdot \vec{\mu}_{23} / |\vec{\mu}_{12}||\vec{\mu}_{23}| = \cos\theta$, where $\theta$ is the angle between the two dipole moments; $\eta_\phi = \eta e^{i\phi}$ $\phi = \phi_p - \phi_c$ is the relative phase between the probe field and the coupling field.

Because of the presence of SGC, the optical properties of the system not only depend on the intensity and frequency detuning of the laser fields but also on their phase. Therefore, the Rabi frequencies are treated as complex parameters. In the slowly varying envelope approximation and the rotating wave approximation, the wave equation form of the probe field is expressed as:

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

where $\alpha=\dfrac{\omega_p N\left|d_{31}\right|^2}{4\varepsilon_0 c\hbar\gamma_{31}}$ is the propagation constant. The moving frame was considered with the laser pulse by setting $\xi$ = z and $\tau=t-z/c$, where c is the light speed in vacuum. In this frame, equations (1-6) will have a similar form by substitution t = $\tau$ and z = $\xi$, while equation (7) is rewritten [15]:

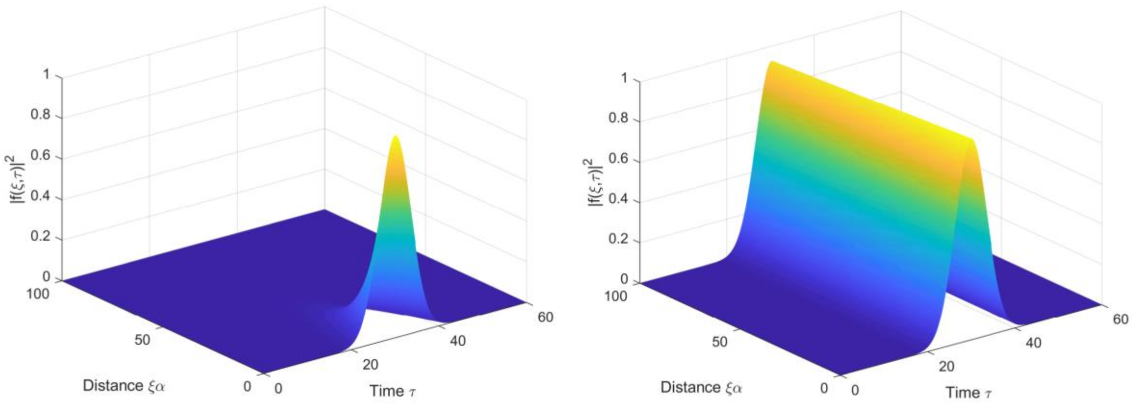
$$\frac{\partial f(\xi,\tau)}{\partial\xi}=\frac{i\alpha\gamma_{21}}{\Omega_{p0}}\rho_{21}(\xi,\tau) \quad (8)$$

Equations (1-6) and (8) are used to study the propagation and all-optical switching dynamics of the probe pulse under different values of the system parameters.

### 3. Theoretical model and basic equations

In this section, to study the pulse propagation dynamics and all-optical switching of the probe laser field, the system of Maxwell-Bloch equations (1-6) and (8) were numerically solved on the space-time grid by using the equation fourth-order Runge-Kutta method and finite difference method. The numerical solution program using Matlab software is developed based on our previous work [15-16]. The initial condition assumes that all atoms start in the ground state $\left|1\right\rangle$, i.e., $\rho_{11}(\xi, \tau = 0) = 1$, and the boundary condition of the probe pulse is assumed to have the form of a Gaussian-type pulse $f\left(\xi=0,\tau\right)=\exp\left[-\left(\ln 2\right)\left(\tau-30\right)^2/\tau_0^2\right]$, where $\tau_0=6/\gamma_{21}$ is the temporal width of the Gaussian pulse at the input ($\xi = 0$) in the atomic medium.

Firstly, the spatio-temporal evolution of the normalized probe pulse envelope intensity $\left|f\left(\xi,\tau\right)\right|^2$ have been plotted in two cases: the coupling field is off (a) and on (b). The first case shows that when the coupling field is turned off, the probe pulse is absorbed and attenuated very quickly when propagating inside the medium over a very short distance, as shown in Figure 2(a). In the second case, when the coupling field is turned on Figure 2(b), the shape of the probe pulse is maintained and hence it can propagate without loss when entering the medium. This can be explained by the fact that when the coupling field is turned on, there is quantum interference in the atomic system, and the electromagnetically induced transparency effect is formed. The medium then becomes transparent to the probe beam. Therefore, the pulse propagates without being absorbed.

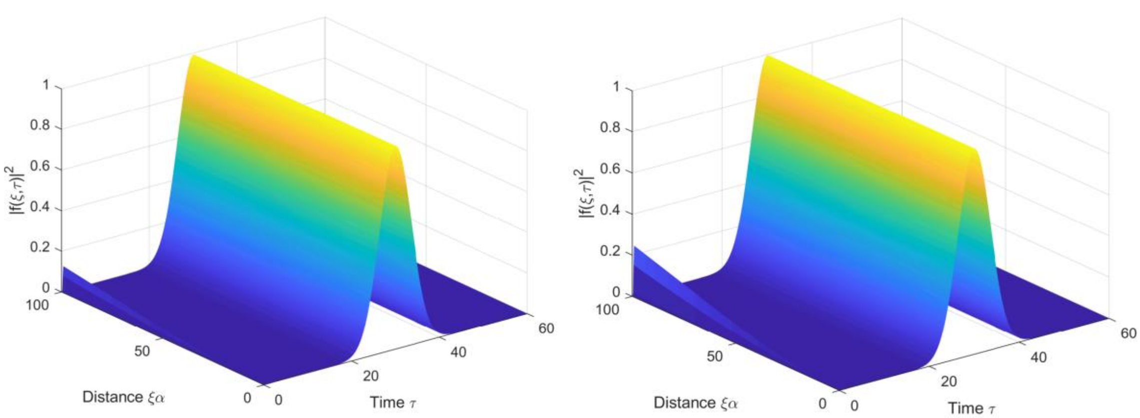



**(a)** **(b)**

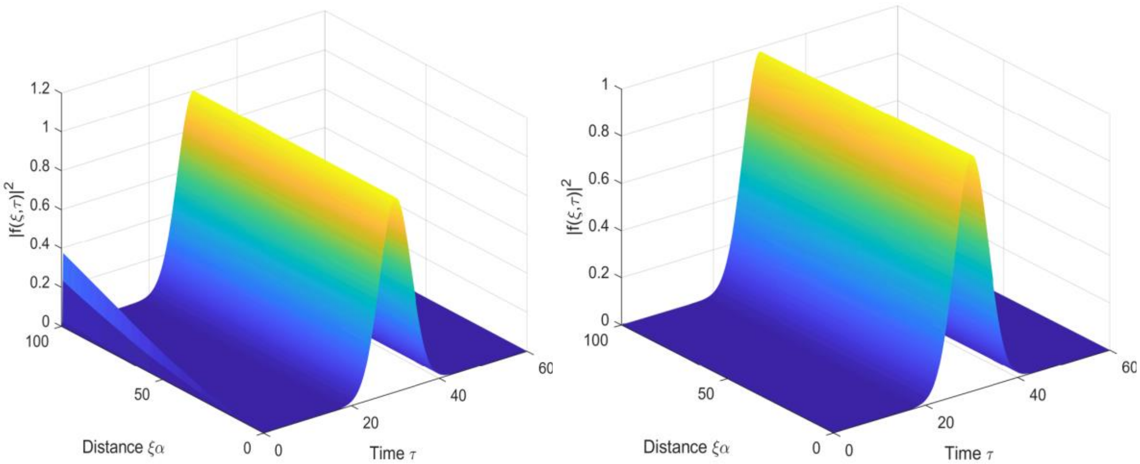
**Figure 2:** *Spatio-temporal evolution of the normalized probe laser pulse intensity when* ***(a)*** *the coupling field is turned off and* ***(b)*** *turned on. Other parameters are $\Omega_{p0} = 0.1\ \gamma_{21}$, $\Omega_c = 10\ \gamma_{21}$, $p = 0$, $R = 0.2\ \gamma_{21}$, $\Delta_p = \Delta_c = 0$, $\phi = \pi/3$, and $\gamma_{32} = 0.5\ \gamma_{21}$, respectively. Here, the time $\tau$ has units of $\gamma_{21}$ and the propagation distance $\xi$ has units of $\alpha^{-1}$*

Next, the influence of SGC parameter on the propagation pulse shape in the presence of relative phase $\phi$ and the incoherent pumping R was studied, as shown in Figure 3. The other parameters have been chosen as $\Omega_c = 10\ \gamma_{21}$, $R = 0.2\ \gamma_{21}$ and the time evolution of the normalized probe pulse intensity $|f(\xi,\tau)|^2$ at different values of the parameter p was considered. Figure 3(a) illustrates that when the presence of SGC effect (with p = 0.5), the envelope of the probe laser pulse appears oscillations at the front edge of the pulse. The amplitude of these oscillations increases simultaneously with the increase of the propagation distance and the increase of the parameter p as seen in Figure 3(b-c), corresponding to the values p = 0.7 and 0.866, respectively. This shows that SGC significantly influences both the absorption and dispersion spectrum of the probe laser pulse.

However, these oscillations can be eliminated with the presence of relative phase as seen in Figure 3(d). That is, when choosing a suitable value of relative phase ($\phi = \pi/2$), the oscillations caused by SGC reduce and sustain steady pulse propagation in the three-level atomic medium in the presence of a non-coherent pump.




**(a)** **(b)**




**(c)** **(d)**

**Figure 3:** *Spatio-temporal evolution of the normalized probe pulse intensity for various values of the interference parameter p:* ***(a)*** *[p = 0.5, R = 0 .2 $\gamma_{21}$ and $\phi$= 0];* ***(b)*** *[p = 0.7, R = 0 .2 $\gamma_{21}$ and $\phi$= 0];* ***(c)*** *[p = 0.866, 0 .2 $\gamma_{21}$ and $\phi$= 0];* ***(d)*** *[p = 0.86, R = 0.2 $\gamma_{21}$ and $\phi$= $\pi/2$].*
*Other parameters are chosen as shown in Figure 2*

Finally, the all-optical switching of the probe field was studied under the modulation of the switching coupling field at different values of the SGC parameter in the presence of relative phase and incoherent pumping as shown in Figure 4. Here, the probe field is assumed to be a continuous wave and the switching coupling field is a quasi-square pulse of the form: $\Omega_c(\tau) = \Omega_{c0}\{1 - 0.5\tanh[0.4(\tau - 10)] + 0.5\tanh[0.4(\tau-35)] - 0.5\tanh[0.4(\tau-60)] + 0.5\tanh[0.4(\tau-85)]\}$, normalized by the value $\Omega_{c0} = 10\gamma_{21}$, and modulated period around $50/\gamma_{21}$.

As seen in Figure 4, the probe field (blue solid line) is switched "On-Off" corresponds to the "On-Off" modulation of the switching coupling field (red dashed line). The results demonstrated that the SGC parameter strongly influences the switching process of the probe field.

Specifically, when the SGC effect is absent, p = 0 [see Figure 4(a)], the switching signal of the probe field has a nearly square shape and high switching efficiency. However, when considering the influence of parameter p: p= 0.5, 0.7 and 0.866 corresponding to Figures 4(b), 4(c), and 4(d), the results show that there is the appearance of oscillations at the leading edge of the probe pulse and cannot create a nearly square pulse shape like the switching pulse $\Omega_c$. The reason for the appearance of oscillations at the leading-edge peak of the probe pulse can be explained by the influence of SGC causing the asymmetry of the atomic medium, so the response of the medium is also quite sensitive to the phase of the laser fields and tents to the coherence between levels $|1\rangle$ and $|3\rangle$ to decrease (this was also demonstrated in the case of Figure 3).

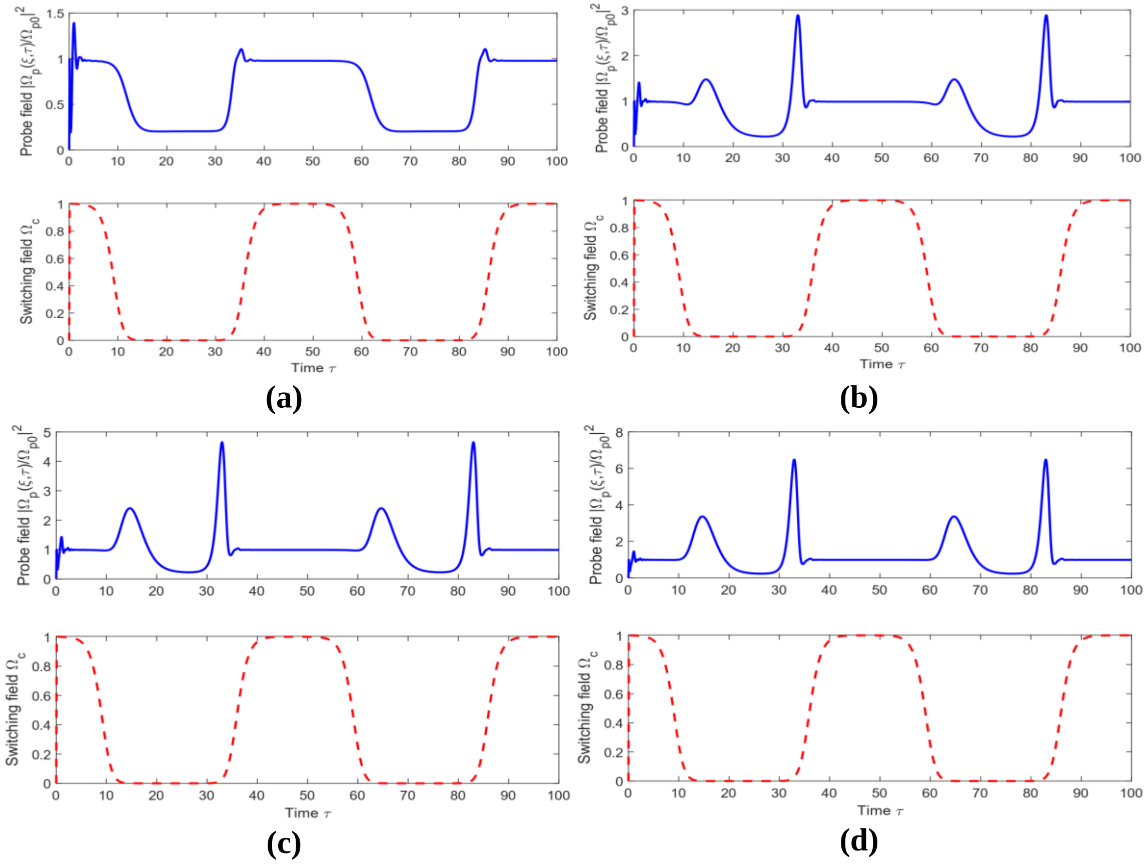



***Figure 4:*** *Time evolution of the probe beam after a propagation distance of $\xi_\alpha = 100$ at different values of the SGC parameter:* ***(a)*** *p = 0;* ***(b)*** *p = 0.5;* ***(c)*** *p = 0.7;* ***(d)*** *p = 0.86. Other parameters are selected as shown in Figure 3*

## 4. Conclusion

In this paper, we have studied the dynamics of the pulse propagation process and all-optical switching of the probe field in a three-level ladder-type atomic medium under the influence of SGC, incoherent pumping and relative phase. The results show that the propagation of the probe pulse is stable in the electromagnetic induction transparent medium. The oscillations at the leading edge of the probe pulse increase as the propagation distance and SGC interference parameter also increase. In particular, these oscillations can be significantly reduced with the participation of incoherent pumping and relative phase. Furthermore, all-optical switching of the probe field is realized through On-Off turning of the switching coupling field. The results obtained in this model can be useful for realizing all-optical switching in quantum optical information processing applications.

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## TÓM TẮT

## ẢNH HƯỞNG CỦA ĐỘ KẾT HỢP ĐƯỢC TẠO BỞI PHÁT XẠ TỰ PHÁT VÀ BƠM KHÔNG KẾT HỢP LÊN CHUYỂN MẠCH TOÀN QUANG TRONG MÔI TRƯỜNG NGUYÊN TỬ BA MỨC BẬC THANG KHI CÓ MẶT CỦA PHA TƯƠNG ĐỐI

**Lương Thị Yến Nga[2], Nguyễn Huy Bằng[2], Lê Thị Dung[2], Hoàng Minh Đồng[1], Trang Huỳnh Đăng Khoa[1], Nguyễn Thị Thu Hiền[1, 2,*]**

*[1]Trường Đại học Công Thương TP. Hồ Chí Minh, Việt Nam*

*[2]Trường Đại học Vinh, Việt Nam*

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Bài báo trình bày kết quả nghiên cứu ảnh hưởng của độ kết hợp được tạo bởi sự phát xạ tự phát (spontaneously generated coherence - SGC) lên sự lan truyền xung laser dò trong hệ nguyên tử ba mức bậc thang khi có mặt pha tương đối của các trường laser và trường bơm không kết hợp. Kết quả cho thấy khi bật trường laser điều khiển thì môi trường hình thành hiệu ứng trong suốt cảm ứng điện từ (electromagnetically induced transparency - EIT) và do đó sự lan truyền xung laser dò có dạng giống như soliton. Ngược lại, trường laser dò bị suy hao nhanh khi tắt trường laser điều khiển. Đặc điểm này cho phép tạo ra cơ chế "tắt" và "bật" trường laser dò thông qua việc "tắt" và "bật" trường laser điều khiển - tức là cơ chế chuyển mạch toàn quang dựa vào EIT. Bên cạnh cường độ và tần số, trường laser còn được đặc trưng bởi sự phân cực (gây ra hiệu ứng SGC) và pha. Hiệu ứng EIT có bản chất của sự giao thoa lượng tử nên rất nhạy với sự thay đổi của sự phân cực, đặc biệt là khi có mặt của pha tương đối giữa các trường laser. Do đó, chúng cũng ảnh hưởng đáng kể lên sự lan truyền xung và hiệu suất chuyển mạch quang. Các kết quả nghiên cứu có thể hữu ích cho quan sát thực nghiệm hoặc các ứng dụng trong các thiết bị quang tử như cổng logic, bộ xử lý thông tin quang lượng tử và máy tính lượng tử.

**Từ khoá:** Chuyển mạch toàn quang; môi trường EIT; giao thoa lượng tử; hệ ba mức bậc thang.