PROPAGATION OF A LASER PULSE UNDER ELECTROMAGNETICALLY INDUCED TRANSPARENCY CONDITIONS

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Abstract: We investigate the propagation dynamics of a pair of probe and coupling laser pulses in a three-level type-V atomic medium under the condition of electromagnetically induced transparency (EIT) by numerical solving the Maxwell-Bloch equations for atoms and fields. Influences of the intensity and pulse area of the coupling laser on the EIT formation of probe laser pulse are studied in a wide region from *micro*- to *pico-second* of pulse duration. It is found that a nearly solition pulse can be established at the smallest pulse area in the *pico-second* region and with the largest pulse area in the *micro-second* region. These results can be important for applications in all-optical switching, and quantum information processing and transmission.

1. Introduction

Over the last years, quantum coherence and interference effects in quantum optics and atomic physics have been of great research interest because of their interesting phenomena and potential applications in quantum engineering and optical communication. Much of the interest in this topic focuses on coherent control of the absorption, dispersion, and nonlinearity coefficients under the conditions of electromagnetically induced transparency (EIT) [1], [2]. Due to the unusual optical properties of the EIT medium have opened new topics as enhancement of Kerr nonlinearity [3] and nonlinear optics at low light level [4], all-optical switching and bistability [5], and so on.

In addition to studies in a steady regime, dynamical processes of light pulses propagating in EIT media are also interesting for researchers because of their potential applications. Several early works which are pioneered in a study on pulse propagation in a three-level lambda system under the EIT condition are proposed by Harris *et al*. [6]. They observed a nearly EIT shape of a light pulse with energy preparation loss at the front edge of the pulse. Since then, numerous works have been performed for several aspects, *e.g.*, dynamical control of light pulse propagation [7], the influence of the relative phase on the probe propagation [8], *etc*.

Most recently, the effects of coupling pulse area and intensity on probe pulse propagation under conditions EIT in a three-level lambda-type and cascade-type atomic medium have been studied in Ref. [9], [10]. In Ref [10], we were shown that a nearly solition pulse can be established by the increase in the peak intensity of the coupling

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laser pulse in the pulse different region. In this paper, we use the same method discussed in Ref. [10] but the model considered in a three-level V-type atomic medium. We also find that under EIT conditions, the probe pulse propagates to similar as soliton pulse, *i.e.*, distortion-free propagation of an optical pulse in an opaque atomic medium.

The paper is organized as follows. In Section 2 we introduce the theoretical model. To describe the propagation dynamic, we utilize the Maxwell-Bloch equations for atoms and fields and numerically solve them on a spatio-temporal grid. In Section 3 we present and discuss representative numerical results for the interaction of a pair of the probe and coupling laser pulse with a three-level V-type atom. We examine the effect of the laser parameters such as coupling pulse area, and laser intensity on the temporal and spatial propagation dynamics of the probe laser pulse. Finally, concluding remarks are given in Section 4.

2. Theoretical model

We consider a V-type three-level scheme excited by two probe and coupling laser fields as shown in Fig. 1. Here, $|1\rangle$ is the ground state, $|2\rangle$ and $|3\rangle$ are the excited states. The dipole allowed transitions are between states $|1\rangle$ and $|2\rangle$, and $|3\rangle$, whereas the transition $|2\rangle \leftrightarrow |3\rangle$ is dipole forbidden. We denote γ_{21} and γ_{31} being the decay rate of the states $|2\rangle$ and $|3\rangle$, respectively. A weak probe laser pulse (with frequency ω_p and field amplitude E_p) drives the transition $|1\rangle \leftrightarrow |3\rangle$, and an intense coupling laser pulse (with frequency ω_c and field amplitude E_c) excites the transition $|1\rangle \leftrightarrow |2\rangle$. Using the rotating-wave and the electric dipole approximations, the interaction Hamiltonian of the system in the interaction picture can be written as (with the assumption of $\hbar$ =1):

$$H = \sum_{i=1}^{3} \hbar\omega_i |i\rangle\langle i| + \Omega_p(z,t)e^{ik_p z - i\omega_p t}|1\rangle\langle 3| + \Omega_c(z,t)e^{ik_c z - i\omega_c t}|1\rangle\langle 2| + c.\mathrm{c}, \tag{1}$$

here, $\Omega_p(z,t) = 2d_{31}E_p f_p(z,t)/\hbar$ and $\Omega_c(z,t) = 2d_{21}E_c f_c(z,t)/\hbar$ are Rabi frequencies induced by the probe and coupling laser pulses, respectively; d_{31} and d_{21} are the dipole matrix elements for the transitions $|1\rangle \leftrightarrow |3\rangle$ and $|1\rangle \leftrightarrow |2\rangle$, respectively.

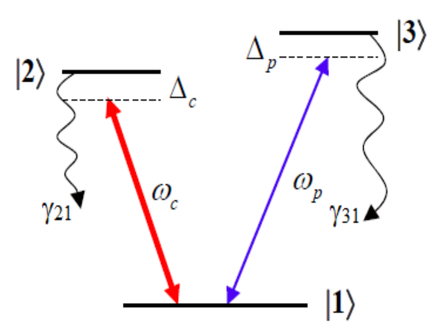

Fig. 1: *Scheme of a three-level V-type atomic system interacting with two probe and coupling lasers*

In the framework of the semi-classical theory, the evolution versus time of the density matrix equations for the three-level atomic system interacting with two laser fields in the dipole and rotating wave approximations has the form [10]:

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + \Lambda\rho . \tag{2}$$

and the relevant density matrix equations obtained for the three-level vee-type system are given as follow:

$$\dot{\rho}_{11} = \gamma_{31}\rho_{33} + \gamma_{21}\rho_{22} + \frac{i}{2}\Omega_c^*\rho_{21} - \frac{i}{2}\Omega_c\rho_{12} + \frac{i}{2}\Omega_p^*\rho_{31} - \frac{i}{2}\Omega_p\rho_{13}, \tag{3a}$$

$$\dot{\rho}_{22} = -\gamma_{21}\rho_{22} + \frac{i}{2}\Omega_c\rho_{12} - \frac{i}{2}\Omega_c^*\rho_{21}, \tag{3b}$$

$$\dot{\rho}_{33} = -\gamma_{31}\rho_{33} + \frac{i}{2}\Omega_p\rho_{13} - \frac{i}{2}\Omega_p^*\rho_{31}, \tag{3c}$$

$$\dot{\rho}_{21} = -\left(i\Delta_c + \frac{\gamma_{21}}{2}\right)\rho_{21} + \frac{i}{2}\Omega_c(\rho_{11} - \rho_{22}) - \frac{i}{2}\Omega_p\rho_{23}, \tag{3d}$$

$$\dot{\rho}_{31} = -\left(i\Delta_p + \frac{\gamma_{31}}{2}\right)\rho_{31} + \frac{i}{2}\Omega_p(\rho_{11} - \rho_{33}) - \frac{i}{2}\Omega_c\rho_{32}, \tag{3e}$$

$$\dot{\rho}_{32} = -\left[i\left(\Delta_p - \Delta_c\right) + \frac{\gamma_{21} + \gamma_{31}}{2}\right]\rho_{32} - \frac{i}{2}\Omega_c^*\rho_{31} + \frac{i}{2}\Omega_p\rho_{12}, \tag{3f}$$

where, the matrix elements obey conjugated and normalized conditions, namely $\rho_{ij} = \rho_{ij}^*$ ($i \neq j$), and $\rho_{11} + \rho_{22} + \rho_{33} = 1$, and $\Delta_p = \omega_p - \omega_{31}$, $\Delta_c = \omega_c - \omega_{21}$ are the probe and coupling frequency detunings, respectively.

In order to study the dynamics of laser pulses propagating in the medium, the Maxwell wave equation under the slowly varying envelope approximation is given by:

$$\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)\vec{E}(z,t) = \frac{i\omega_m}{2\varepsilon_0 c}\vec{P}_m(z,t) \tag{4}$$

with m = p or c hereafter, when Doppler broadening has been ignored, the of macroscopic polarization of the medium $\vec{P}_m(z,t)$ is given by

$$\vec{P}_m(z,t) = Nd_{n1}\rho_{n1}(z,t)e^{i(\omega_m t - k_m z)}, \text{ with } n = 2 \text{ or } 3 \tag{5}$$

where, N is the density of the particle. Substituting Eq. (5) into Eq. (4) we obtain the following equations for the propagation of the Rabi frequencies:

$$\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)\Omega_p(z,t) = 2i\mu_p\rho_{31}(z,t), \tag{6a}$$

$$\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)\Omega_c(z,t) = 2i\mu_c\rho_{21}(z,t), \tag{6b}$$

here, $\mu_m = \dfrac{\omega_m N |d_{n1}|^2}{2\varepsilon_0 c\hbar}$ is the propagation constant and n = 2 or 3, and ε_0 is the vacuum permittivity. It is convenient to transform Eqs. (3) and (6) in the local frame where $\xi = z$ and $\tau = t - z/c$, with c is the speed of light in vacuum. In this frame Eqs. (3) will the same with the substitution $t \to \tau$ and $z \to \xi$, while Eqs. (6) are rewritten as:

$$\frac{\partial}{\partial \xi}\Omega_p(\xi,\tau) = 2i\mu_p \rho_{31}(\xi,\tau), \tag{7a}$$

$$\frac{\partial}{\partial \xi}\Omega_c(\xi,\tau) = 2i\mu_c \rho_{21}(\xi,\tau). \tag{7b}$$

The Eqs. (3) and (7) govern the spatial-temporal evolution of the laser pulses in the medium.

3. Result and discussion

In this section, we numerically solve the coupled Bloch-Maxwell equations (3) and (7) on a space-time grid by using a combination of the four-order Runge-Kutta and finite difference methods. The propagation length is represented in units of $\mu_p \xi$ which is the so-called optical depth [6]. The temporal profiles of the field at the entrance to the medium is a Gaussian function, *i.e.,*

$$f(\xi = 0, \tau) = e^{-\pi\left(\frac{\tau}{\tau_0}\right)^2}, \tag{8}$$

with τ_0 is the pulse temporal width of a single laser pulse which is assumed to be identical for both probe and coupling lasers.

First of all, we investigate the influence of the intensity and pulse area of the coupling laser on the spatio-temporal evolution of the probe pulse envelope $\Omega_p(\xi,\tau)$ in the nanosecond pulse duration region as shown in Fig. 2, here, the coupling pulse areas and intensity are given as in figures. The pulse duration is fixed at τ_0 = 25 ns, which is approximate to the life time of the excited states. The parameters we choose for Fig. 2 are: Ω_p = 0.04 GHz, $\Delta_p = \Delta_c = 0$, and $\gamma_{21} = \gamma_{31}$ = 6MHz, for all graphs. Since the pulse duration τ_0 is fixed at 25 ns, hence such growing of the pulse area leads to an increase in the coupling Rabi frequency Ω_{c0} from 1 GHz to 200 GHz. It is apparent that for a small value of the pulse area ($\Omega_{c0}\tau_0 \leq 100$) the probe pulse is strongly oscillating at the peak and shape distorted due to resonant absorption in an atomic medium, i.e., there is no EIT effect (Fig. 2a and Fig. 2b). When the pulse area (thus the pulse peak) of the coupling beam increases, although the leading edge of the probe pulse is still distorted but the ending edge approaches earlier transparency (Figs. 2c and 2d). As we explained [10], such distortion of the leading edge is due to the energy loss to prepare for the EIT formation of probe pulse [6], [9], [10]. In particular, when the pulse area reaches to the value of $\Omega_{c0}\tau_0 = 5\times10^3$ (Fig. 2f), the probe pulse is almost unchanged, namely an ideal EIT or nearly soliton is established. These behaviors of evolution have good agreement with obtained those in [10] for three-level cascade-type atomic configuration.

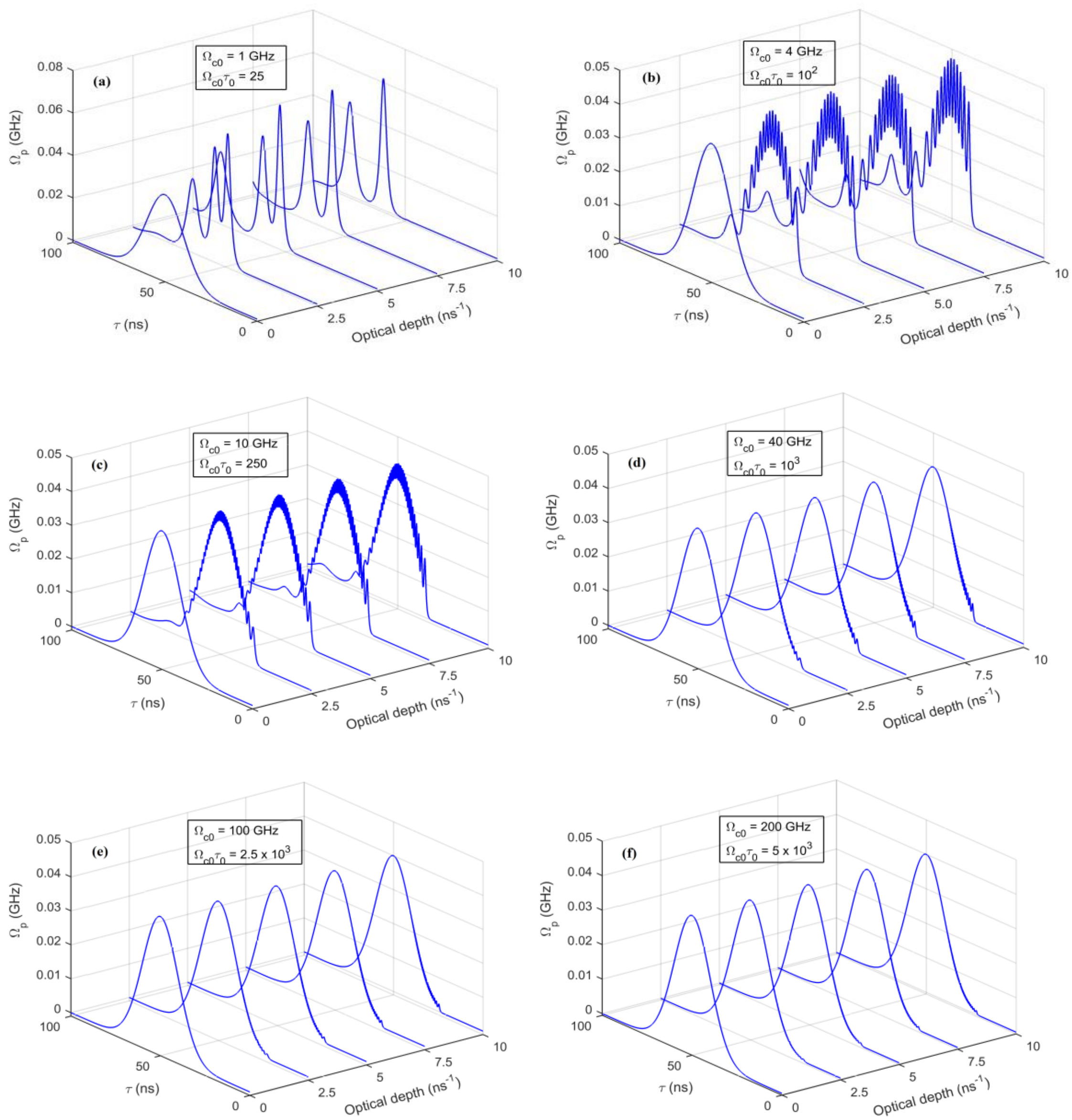

Fig. 2: *Space-time evolution of probe laser field* $\Omega_p(\xi,\tau)$ *at different optical depths* $\mu_p\xi$ = *0, 2.5, 5, 7.5 and 10 ns*$^{-1}$ *when* τ_0 *= 25 ns and the pulse areas are given as in figures. The employed parameters are* Ω_p *= 0.04 GHz,* $\Delta_p = \Delta_c = 0$*, and* $\gamma_{21} = \gamma_{31}$*= 6MHz, for all graphs.*

Next, in order to see the further influence of the coupling laser pulses duration τ_0 on the propagation dynamics of the probe laser pulse, we simulate the spatiotemporal pulse shape in the *micro-second* region (pulse width τ_0 = 0.25 μs) and in the *pico-second* region (pulse width τ_0 = 25 *ps*) as shown in Fig. 3 and Fig. 4, respectively. It is found that by increasing the coupling laser intensity, we can also reach to the ideal EIT of the probe pulse. By comparing Fig. 2 with Fig. 3 and Fig. 4 shows that the ideal EIT effect can be easily achieved with a smaller pulse area in *ps* region but with a larger pulse area in μs

and *ns*. This can be explained is due to the lifetime of excited states (about 25 ns) is short compared with the pulse duration in *μs* region, hence the laser pulse is damped and strongly absorbed [9], [10]. However, in order to obtain the EIT effect in *ps* region, the coupling laser intensity is much larger than that in other regions. As it is clearly known that in *ps* region, a period which the atoms experience a pulse is much smaller than that in other regions.

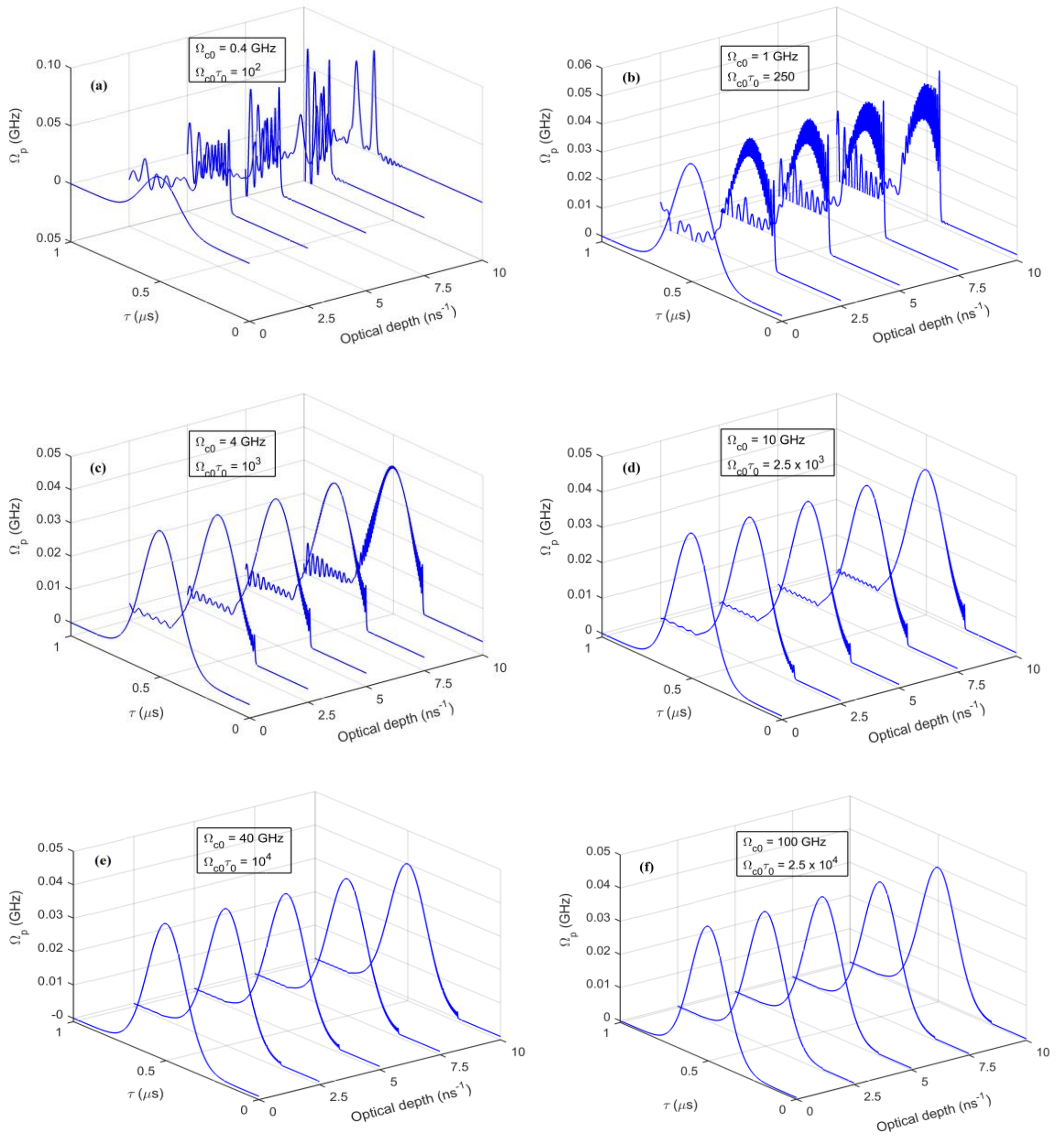

Fig. 3: *The space-time evolution of probe laser field* $\Omega_p(\xi,\tau)$ *at different optical depths* $\mu_p\xi$ *= 0, 2.5, 5, 7.5 and 10 ns*$^{-1}$ *when* τ_0 *= 0.25* μ*s, and the pulse areas are given as in figures. Other parameters are the same as those in Fig. 2.*

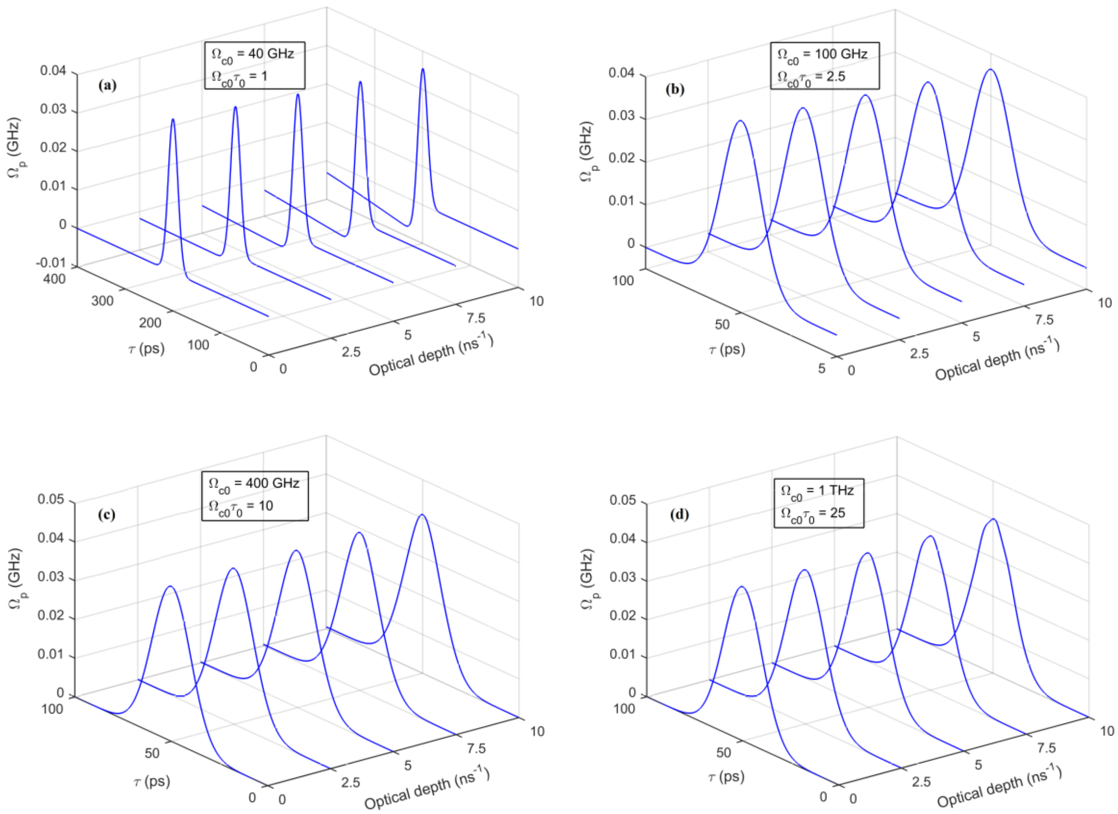

Fig. 4: *Space-time evolution of probe laser field* $\Omega_p(\xi,\tau)$ *at different optical depths* $\mu_p\xi$ *= 0, 2.5, 5, 7.5 and 10* ns^{-1} *when* τ_0 *= 25 ps and the pulse areas are given as in figures. Other parameters are the same as those in Fig. 2.*

4. Conclusion

We have investigated the probe pulse propagation in a three-level V-type atomic medium. By consideration of the influence of the intensity and pulse area of the coupling laser pulse, we found the conditions that the atomic medium becomes transparency for the probe laser in a wide region from micro- to pico-second of pulse duration. With an appropriate parameter of the coupling pulse area, the EIT effect of probe pulse is created in every pulse region, *i.e.*, near soliton pulses are obtained. Additionally, the EIT effect for long pulse durations is established at pulse areas are larger than that of short pulse durations. These results suggest the relative applications in all-optical switching, and information processing and transmission.

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TÓM TẮT

SỰ LAN TRUYỀN CÁC XUNG LASER KHI CÓ HIỆU ỨNG TRONG SUỐT CẢM ỨNG ĐIỆN TỪ

Chúng tôi nghiên cứu động học lan truyền của cặp xung laser dò và laser điều khiển trong môi trường ba mức cấu hình chữ V khi có hiệu ứng trong suốt cảm ứng điện từ (EIT) bằng cách giải số phương trình Maxwell-Bloch. Ảnh hưởng của cường độ và diện tích xung laser điều khiển lên sự hình thành EIT của xung laser dò là được nghiên cứu trong miền rộng từ *micro* giây tới *pico giây* của độ rộng xung. Kết quả cho thấy rằng, các xung gần giống soliton có thể được tạo thành với độ rộng xung trong miền từ *pico giây* đến *micro giây*. Các kết quả là quan trọng cho các ứng dụng về chuyển mạch toàn quang, các quá trình truyền và xử lý thông tin lượng tử.