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Ultra slow light propagation without any control light field*

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Without need of another control light, this paper analyses in a time-dependent way a new scheme to achieve ultraslow propagation of the input probe field through a medium composed of two-level atoms where their upper level is split into two hyperfine sub-levels via some applied static field such as a DC magnetic or a DC electric field or whatever other static field.

Keywords: electromagnetically induced transparency, ultraslow light
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In the past few years, the technique of electromagnetically induced transparency (EIT)[1−28] has received a great attention mainly because it can significantly reduce absorption of an optical field tuned to a strong one-photon resonance, and leads to ultraslow propagation of the optical field. Such an index manipulation and channel opening technique is expected to have potentially very important applications in various fields such as quantum information storage and retrieval, controllable optical delay lines (true time delay for synthetic aperture radar, buffers for optical processors and routers), enhancement of nonlinear effects for optical switching, all-optical transistor, and optical isolation.[1−28]

In this paper, we propose a new scheme to achieve ultraslow propagation of the input field without need of another control field as shown in Fig.1, specifically, we consider an input pulsed light to propagate through a medium composed of two-level atoms where their upper level is split into two hyperfine sub-levels via some applied static fields such as a DC magnetic or electric field or whatever other static field.

Our motivation is two-fold. First, we want to demonstrate that ultraslow propagation of the input field can be achieved without need of another control field. It is sometimes more convenient to use other means instead of a control light to perform the index manipulation and channel opening in some applications such as controllable optical delay lines (true time delay for synthetic aperture radar, buffers for optical processors and routers) and optical switching. For instance, in order to prevent the enemy's radar detection of the accurate position of an air fighter, one trick is to make a coating on the surface of air fighter so that the radar light travels through the coating with an ultraslow velocity. Obviously, applying a control light over the whole surface of the air fighter is extremely difficult (if not impossible) while a much simpler method is to apply a DC voltage across the coating throughout the surface. Second, it is instructive to test the picture if EIT can be explained as a result of the quantum destructive interference of the two channels formed by using a strong on-resonance control laser to split the terminal state of the one-photon transition for the probe laser into an Autler–Townes doublet. Our results demonstrate that such a picture, though captures some characteristics, misses certain essential ingredients of EIT originating from the two drastically different decay or dephasing rates.

We start with the Hamiltonian

$$H = \sum_{j=0,a,b} \epsilon_j |j\rangle\langle j| - \hbar \left[\Omega \, \mathrm{e}^{\mathrm{i}(k_1 z - \omega_1 t)} \left(|a\rangle + |b\rangle \right) \langle 0| + \mathrm{h.c.} \right], \quad (1)$$

where ϵ_j is the energy of state $|j\rangle$, and Ω, ω_1 and k_1 denote the Rabi frequency, frequency and wavenumber of the pulsed light field respectively. Defining atomic state as $|\Psi\rangle = [A_0|0\rangle\langle 0| + (A_a|a\rangle\langle a| +$

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$A_b|b\rangle\langle b|)\exp(\mathrm{i}k_\mathrm{l}\,z-\mathrm{i}\omega_\mathrm{l}\,t)]\exp(-\mathrm{i}\epsilon_0 t/\hbar)$, we then have the atomic equations of motion as

$$\frac{\partial A_0}{\partial t}=\mathrm{i}(A_a+A_b)\Omega^*, \tag{2}$$

$$\frac{\partial A_a}{\partial t}=\mathrm{i}(\omega_{ba}+\Delta+\mathrm{i}\gamma_a)A_a+\mathrm{i}\Omega A_0, \tag{3}$$

$$\frac{\partial A_b}{\partial t}=\mathrm{i}(\Delta-\omega_{ba}+\mathrm{i}\gamma_b)A_b+\mathrm{i}\Omega A_0, \tag{4}$$

where γ_j is the decay rate of state $|j\rangle$ $(j=a,b)$, $2\hbar\omega_{ba}$ is the energy splitting of the upper two sub-levels a and b (see Fig.1), and $\Delta=\omega_\mathrm{l}-(\epsilon_1-\epsilon_0)/\hbar$ is the detuning.

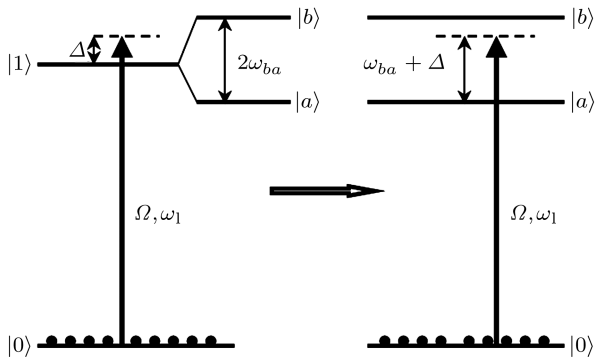


Fig.1. Schematic of two-level atoms interacting with a pulsed light of frequency ω_l and Rabi frequency 2Ω. Δ is the detuning. The splitting of the upper atomic level $|1\rangle$ into a doublet are due to certain applied static field, say, a static electric field E, and hence the energy splitting $\hbar\omega_{ba}\propto E$.

To the first order of the field Ω and assuming that the atomic system is initially in the ground state $|0\rangle$, we have the results $A_0\simeq 1$ and

$$\alpha_a=-\frac{\Lambda}{\omega+\omega_{ba}+\Delta+\mathrm{i}\,\gamma_a},$$
$$\alpha_b=\frac{\Lambda}{\omega_{ba}-\Delta-\omega-\mathrm{i}\,\gamma_b}, \tag{5}$$

where α_j and Λ are the Fourier transforms of A_j and Ω respectively and ω is the Fourier transform variable.

The Fourier transform of wave equation is

$$\frac{\partial\Lambda}{\partial z}-\mathrm{i}\frac{\omega}{c}\Lambda=\mathrm{i}(\alpha_a+\alpha_b)\kappa, \tag{6}$$

where $\kappa=2N\omega_\mathrm{l}|D_{10}|^2/(\hbar c)$, N is the atom concentration, and D_{10} is the dipole moment between states $|1\rangle$ and $|0\rangle$.

Substituting Eq.(5) into Eq.(6), we then have the solution for the field as follows,

$$\Lambda(z,\omega)=\Lambda(0,\omega)\exp(\mathrm{i}\,K\,z), \tag{7}$$

$$K=\frac{\omega}{c}+\frac{\kappa}{\omega_{ba}-\Delta-\omega-\mathrm{i}\,\gamma_b}-\frac{\kappa}{\omega_{ba}+\Delta+\omega+\mathrm{i}\,\gamma_a}, \tag{8}$$

where $\Lambda(0,\omega)$ is the Fourier transform of the field Ω at the entrance $z=0$.

Expanding K into the series $K=K_0+\omega/V_\mathrm{g}+\mathcal{O}\left(\omega^2\right)$, and neglecting the terms of the order $\mathcal{O}\left(\omega^2\right)$, and then performing the inverse Fourier transform of Eq.(7), we finally obtain the light field

$$\Omega(z,t)=\Omega(0,t-z/V_\mathrm{g})\exp(\mathrm{i}\,\phi\,z-\alpha\,z/2), \tag{9}$$

where $\phi=\mathrm{Re}(K_0)$, $\alpha/2=\mathrm{Im}(K_0)$ and

$$\phi+\mathrm{i}\frac{\alpha}{2}=\frac{\kappa}{\omega_{ba}-\Delta-\mathrm{i}\,\gamma_b}-\frac{\kappa}{\omega_{ba}+\Delta+\mathrm{i}\,\gamma_a}, \tag{10}$$

$$\frac{1}{V_\mathrm{g}}\simeq\frac{1}{c}+\mathrm{Re}\left[\frac{\kappa}{(\omega_{ba}-\Delta-\mathrm{i}\,\gamma_b)^2}+\frac{\kappa}{(\omega_{ba}+\Delta+\mathrm{i}\,\gamma_a)^2}\right]. \tag{11}$$

Equations (9) and (10–11) explicitly give the analytical expressions of the space-time dependent light field, the corresponding phase shift per unit length ϕ and (energy) absorption coefficient α, and the group velocity V_g.

For the purpose of comparison, let us list the corresponding results for the Λ-type EIT scheme (Fig.2),

$$K_0=\phi+\mathrm{i}\frac{\alpha}{2}=\frac{\kappa(\Delta_t+\mathrm{i}\gamma_2)}{|\Omega_\mathrm{c}|^2-(\Delta+\mathrm{i}\gamma_1)(\Delta_t+\mathrm{i}\gamma_2)}, \tag{12}$$

$$\frac{1}{V_\mathrm{g}}\simeq\frac{1}{c}+\mathrm{Re}\left\{\frac{\kappa[|\Omega_\mathrm{c}|^2+(\Delta_\mathrm{t}+\mathrm{i}\gamma_2)^2]}{[|\Omega_\mathrm{c}|^2-(\Delta+\mathrm{i}\gamma_1)(\Delta_t+\mathrm{i}\gamma_2)]^2}\right\}, \tag{13}$$

where the detunings are $\Delta_\mathrm{t}=\Delta-\Delta_\mathrm{c}$, $\Delta=\omega_\mathrm{p}-(\epsilon_1-\epsilon_0)/\hbar$, $\Delta_\mathrm{c}=\omega_\mathrm{c}-(\epsilon_1-\epsilon_2)/\hbar$, and γ_j is the decay rate of the atomic state $|j\rangle$ $(j=1,2)$. Equations (12–13) can readily be obtained from Ref.[8] by switching off all other fields except for the control and probe fields. Besides, Eq.(5) of Ref.[9] is the equivalent form of our Eq.(12). It is important to note that γ_2 is in fact the decoherence (or dephasing) rate for the states $|2\rangle$ and $|0\rangle$, and $\gamma_2/\gamma_1\leq 10^{-3}$ for typical EIT experiments because $|2\rangle\rightleftharpoons|0\rangle$ are dipole forbidden transitions.

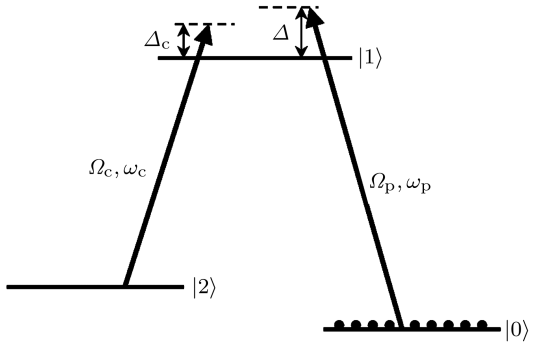


Fig.2. Schematic of Λ-type EIT scheme. The continuous-wave control (pulsed probe) field has frequency ω_c (ω_p) and Rabi frequency $2\Omega_c$ ($2\Omega_p$). $\Delta(\Delta_c)$ is the single photon detuning of the probe (control) field.

Under the condition $\omega_{ba} \gg \max(\gamma_a, \gamma_b)$ ($|\Omega_c|^2 \gg \gamma_1\gamma_2$), Eqs.(10–11) [Eqs.(12–13)] for our new scheme (Λ-type scheme) lead to the results,

$$\alpha_{\rm valley}^{(\rm new)} \simeq \frac{2\kappa\gamma_1}{\omega_{ba}^2},\ \frac{1}{V_{\rm g}^{(\rm new)}} \simeq \frac{1}{c} + \frac{\kappa}{\omega_{ba}^2}, \Delta = 0, \quad (14)$$

$$\alpha_{\rm vallley}^{(\Lambda)} \simeq \frac{2\kappa\gamma_2}{|\Omega_c|^2},\ \frac{1}{V_{\rm g}^{(\Lambda)}} \simeq \frac{1}{c} + \frac{\kappa}{|\Omega_c|^2},$$

$$\Delta = \Delta_c = 0, \quad (15)$$

$$\alpha_{\rm peak}^{(\rm new)} \simeq \frac{4\kappa}{\gamma_1},\ \ \Delta \simeq \pm\omega_{ba}, \quad (16)$$

$$\alpha_{\rm peak}^{(\Lambda)} \simeq \frac{2\kappa}{\gamma_1},\ \ \Delta \simeq \pm|\Omega_c| \text{ and } \Delta_c = 0, \quad (17)$$

where we have taken $\gamma_a = \gamma_b = \gamma_1$ [$\gamma_1 \equiv (\gamma_a + \gamma_b)/2$ in Eq.(14)], the superscript 'new' ('Λ') denotes the results of our new scheme (Λ-type EIT scheme), and the subscript 'valley' ('peak') designates the absorption coefficient evaluated in the middle of the transparency window (at the absorption peaks), see Figs.3–5.

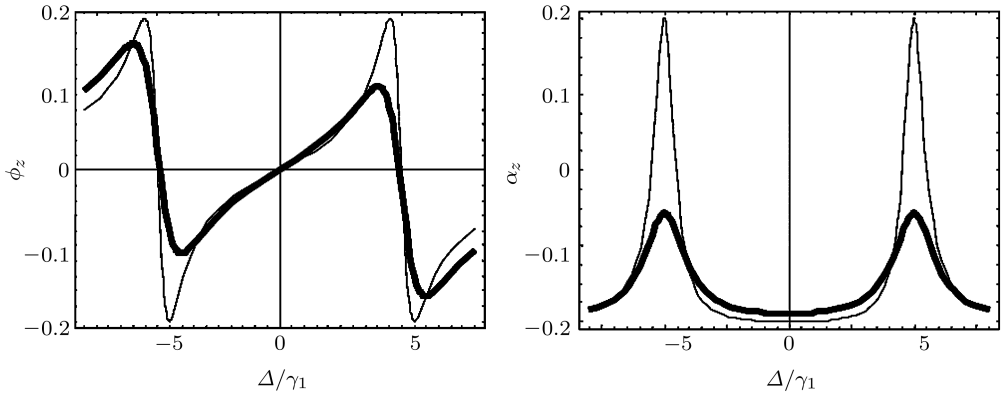


Fig.3. Phase shift ϕ_z (left) or absorption α_z (right) versus detuning Δ/γ_1. The thick (thin) lines are for our (Λ-type EIT) scheme. The common parameters for both schemes are $z = 0.2\,\text{cm}$ and $\kappa/\gamma_1 = 2\,\text{cm}^{-1}$ ($\kappa = 1.2 \times 10^7 \text{cm}^{-1} \cdot \text{s}^{-1}$ for typical Rubidium atom value $\gamma_1 = 6\,\text{MHz}$). The other parameters for our (Λ-type EIT) scheme are $\omega_{ba} = 5\gamma_1$ and $\gamma_a = \gamma_b = \gamma_1$ ($\Delta_c = 0, \Omega_c = 5\gamma_1$ and $\gamma_2 = 0.001\,\gamma_1$). Notice that $\omega_{ba} = \Omega_c$.

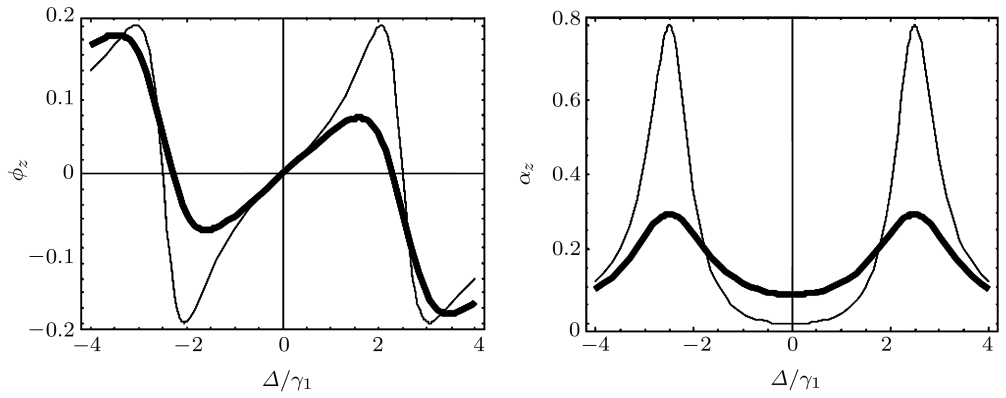


Fig.4. Same as Fig.3 except for $\omega_{ba} = \Omega_c = 2.5\gamma_1$.

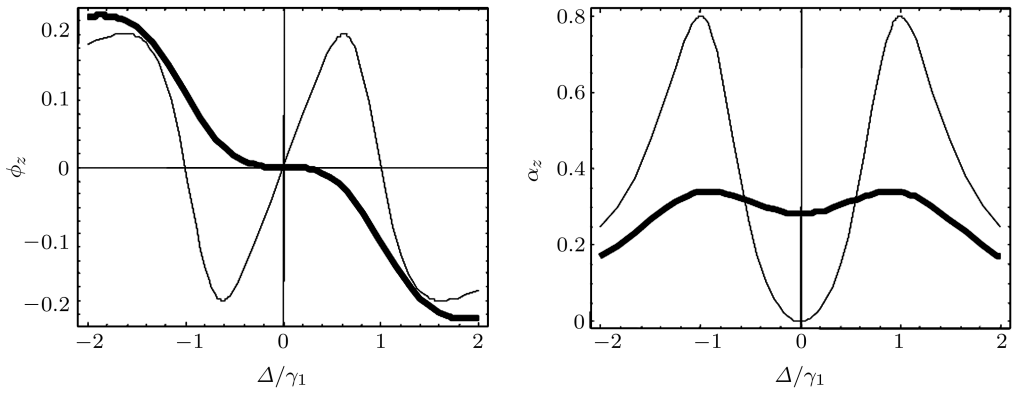


Fig.5. Same as Fig.3 except for $\omega_{ba} = \Omega_c = \gamma_1$.

Equations (11–17) (taking $\omega_{ba} = |\Omega_c|$) and Figs.3–5 clearly demonstrate the similarity and essential differences in the final results of our scheme and the Λ-type EIT scheme. Notice that the slope of phase shift ϕ determines uniquely the group velocity in both schemes, and it has nearly the same value for both schemes in the middle of the transparency window for the parameters shown in Figs.3 and 4. It can be shown that the group velocity of our scheme can have nearly the same value as the group velocity in Λ-type EIT scheme at least for $\omega_{ba} = |\Omega_c| \geq 2.5$ with the typical parameters of Rubidium atoms. For instance, for the parameters given in Fig.4 and all detunings are taken as zero, both schemes gives $V_g/c \simeq 7 \times 10^{-4}$ with $\alpha_z \simeq 0.08$ in our scheme and $\alpha_z \simeq 0.000128$. Increasing κ with other parameters fixed can decrease the group velocity at the expense of increasing absorptions. However, the results of two schemes show two essential differences: 1) EIT scheme is much more efficient than our scheme in reducing the absorption because $\alpha^{(\mathrm{new})}_{\mathrm{vallley}}/\alpha^{(\Lambda)}_{\mathrm{vallley}} \simeq \gamma_1/\gamma_2 \geq 10^3$ as shown by Eqs.(14–17). 2) As shown in Fig.5, the transparency disappears in our scheme while it still exists in EIT scheme when $\omega_{ba} = |\Omega_c|$ is comparable to γ_1. As a matter of fact, there exists pronounced transparency in the EIT scheme even when $|\Omega_c| = 0.1\gamma_1$. This difference also comes from the two drastically different decay rates $\gamma_{1,2}$. There exists transparency when $\omega_{ba} \gg \max(\gamma_a, \gamma_b) \simeq \gamma_1$ or $|\Omega_c|^2 \gg \gamma_1\gamma_2$. Obviously, $|\Omega_c| = 0.1\gamma_1$ satisfies well the condition $|\Omega_c|^2 \gg \gamma_1\gamma_2$ as $\gamma_2/\gamma_1 \leq 10^{-3}$.

In summary, we have proposed and analysed a new scheme to achieve ultraslow propagation of the input field without need of another control field, and compared it with the Λ-type EIT scheme in details.

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