Influence of quantum coherence on propagation of a pulsed light in a triple quantum well

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Abstract: In a triple semiconductor quantum well structure coupled by two external fields, we investigate the influence of atomic coherence induced by external fields and decay interference on the absorption and dispersion of a weak pulsed light, and slow light can be achieved in this system. Quantum well structure behaves as "artificial atom" and its advantage of easy integration makes it has some practical applications.

OCIS codes: (270.1670) Coherent optical effects; (250.5590) Quantum-well, -wire and –dot devices.

References and links

1. M. Phillips and H. Wang, "Electromagnetically induced transparency due to intervalence band coherence in a GaAs quantum well," Opt. Lett. **28**(10), 831–833 (2003).
2. T. Müller, W. Parz, G. Strasser, and K. Unterrainer, "Influence of carrier-carrier interaction on time-dependent intersubband absorption in a semiconductor quantum well," Phys. Rev. B **70**(15), 155324 (2004).
3. J. F. Dynes, M. D. Frogley, J. Rodger, and C. C. Phillips, "Optically mediated coherent population trapping in asymmetric semiconductor quantum wells," Phys. Rev. B **72**(8), 085323 (2005).
4. W. X. Yang, X. X. Yang, and R. K. Lee, "Carrier-envelope-phase dependent coherence in double quantum wells," Opt. Express **17**(18), 15402–15408 (2009).
5. C. R. Lee, Y. Li, F. K. Men, C. Pao, Y. Tsai, and J. Wang, "Model for an inversionless two-color laser," Appl. Phys. Lett. **86**(20), 201112 (2005).
6. H. Schmidt and R. J. Ram, "All-optical wavelength converter and switch based on electromagnetically induced transparency," Appl. Phys. Lett. **76**(22), 3173–3175 (2000).
7. B. S. Ham, "Potential applications of dark resonance to subpicosecond optical switches in hyper-terahertz repetition rates," Appl. Phys. Lett. **78**(22), 3382–3384 (2001).
8. J. M. Tang, J. Levy, and M. E. Flatté, "All-electrical control of single ion spins in a semiconductor," Phys. Rev. Lett. **97**(10), 106803 (2006).
9. X. Lü and J. Wu, "Three-mode entanglement via tunneling-induced interference in a coupled triple-semiconductor quantum-well structure," Phys. Rev. A **82**(1), 012323 (2010).
10. A. Fountoulakis, A. Terzis, and E. Paspalakis, "Coherence phenomena due to double-dark states in a system with decay interference," Phys. Rev. A **73**(3), 033811 (2006).
11. S. E. Economou, R. B. Liu, L. J. Sham, and D. G. Steel, "Unified theory of consequences of spontaneous emission in a Λ system," Phys. Rev. B **71**(19), 195327 (2005).
12. J. F. Dynes, M. D. Frogley, M. Beck, J. Faist, and C. C. Phillips, "AC stark splitting and quantum interference with intersubband transitions in quantum wells," Phys. Rev. Lett. **94**(15), 157403 (2005).
13. H. Schmidt, K. L. Campman, A. C. Gossard, and A. Imamoglu, "Tunneling induced transparency: Fano interference in intersubband transitions," Appl. Phys. Lett. **70**(25), 3455–3457 (1997).
14. E. Paspalakis, N. J. Kylstra, and P. L. Knight, "Transparency induced via decay interference," Phys. Rev. Lett. **82**(10), 2079–2082 (1999).
15. P. R. Berman, "Spontaneously generated coherence and dark states," Phys. Rev. A **72**(3), 035801 (2005).
16. B. K. Ridley, *Quantum Processes in Semiconductors* (Clarendon Press, 1988).
17. Y. Wu, "Two-color ultraslow optical solitons via four-wave mixing in cold-atom media," Phys. Rev. A **71**(5), 053820 (2005).
18. Y. Wu and X. X. Yang, "Electromagnetically induced transparency in V-, Λ-, and cascade-type schemes beyond steady-state analysis," Phys. Rev. A **71**(5), 053806 (2005).
19. S. Yelin, V. A. Sautenkov, M. Kash, G. Welch, and M. Lukin, "Nonlinear optics via double dark resonances," Phys. Rev. A **68**(6), 063801 (2003).
20. M. D. Lukin, S. F. Yelin, M. Fleischhauer, and M. O. Scully, "Quantum interference effects induced by interacting dark resonances," Phys. Rev. A **60**(4), 3225–3228 (1999).

In a semiconductor quantum well structure, quantum coherence and interference produced due to intersubband transitions between the states of an electron confined in this structure have

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induced a lot of interesting and unexpected physical consequences. Some of these consequences are electromagnetically induced transparency (EIT) [1], pulsed-induced quantum interference [2], coherent population trapping [3], carrier-envelope-phase dependent coherence [4], gain without inversion [5]. In addition, the technology of quantum coherence and interference is expected to have potentially important application in various fields such as ultrafast optical switches [6] and quantum switches [7], quantum information storage and retrieval [8], and preparation of entangled state [9].

As a class of quantum coherence and interference, spontaneously generated coherence (SGC) has been studied in atomic system [10] and semiconductor dot system [11]. We know semiconductor quantum well structures possess of intersubband transitions and behave as "artificial atoms" [12]. Due to longitudinal optical phonon emission events at low temperature [3], the population decay occurs. Some research groups have investigated spontaneously generated coherence in quantum well structure [13]. SGC is the interference of spontaneous emission channels, and the existence of such decay interference requires the nonorthogonality of the two dipole moments. The recent studies show that decay interference can affect the EIT, shot-pulse propagation, dark state, etc [14,15]. To the best of our knowledge, no further theoretical and experimental work has been carried out to investigate the influence of SGC on transmission of a pulsed light in a triple semiconductor quantum well driven by external light fields, which motivates us to investigate effect of decay interference.

In this paper, we consider the effect of quantum interference in a triple semiconductor quantum well with one ground subband and three excited subbands when driven by a pump field and a control field. The influence of atomic coherence produced by coherent driving of external fields on the absorption and dispersion of the pulsed field is investigated. In addition, due to longitudinal optical phonon emission, coupling to the lattice phonon spectrum, and interface roughness scattering, these excited subbands take place decay. According to the theory of decay interference, we theoretically study the influence of decay interference on the absorption and dispersion of a pulsed light in a quantum well. The effect of slow light is investigated in this system. Being an attractive quantum coherent medium, semiconductor quantum well structure has its own advantages: strong electron-electron interactions can produce a collective oscillation, which can behave as a single quantum object, and its large transition dipoles give rise to sizeable Rabi frequencies which are large enough to overcome dephasing. In addition, compared with atomic system, semiconductor quantum well structure has an advantage of easy integration, so the manipulation of absorption of light in this system has a more practical value. Our work is based on existing physical model [5,9] and maybe our theoretical studies have some reference value for the future experiments.

We consider a semiconductor quantum well structure that consists of a deep well and two shallow wells. This triple quantum well is shown in Fig. 1(a), where the first excited state in the deep well and the respective ground states in the two shallow wells mix to form three new excited states of this system, and the ground state in the deep well and three excited states created newly are expressed as $|0\rangle$, $|1\rangle$, $|2\rangle$ and $|3\rangle$, respectively, which refer to the electronic wave functions (subbands). For the excited states, there are two different types of dephasing rates; one is population decay rate which is represented by γ_j^p ($j = 1,2,3$), the other is pure dipole dephasing rate which is stood for γ_j^d. For the population decay rate, it is due primarily to longitudinal optical (LO) phonon emission events at low temperature, which is different from atomic system where the excited state spontaneously decays to a lower lying level, that is, population decay rates for atomic system are pure radiative decay. For the pure dipole dephasing rate, it results from a combination of quasielastic interface roughness scattering or acoustic phonon scattering, and this kind of dephasing rate is akin to atomic collisional broadening in gases. The total dephasing rates are expressed as γ_j and are given by $\gamma_j = \gamma_j^p + \gamma_j^d$.

For the dephasing rate in quantum well structure, the dominant phonon contributions come from piezoelectric and Frohlich coupling to acoustic and optical phonon branches,

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respectively. In the two branches of coupling, the intersubband transition couples via the phonon's oscillating electric field [16], so the rates scale with D_{ij}^2 (D_{ij} is transition dipole), just as natural atoms. The dipole dephasing rates of this structure are strongly dependent upon the electronelectron scattering process. For simplicity, we assume our calculation is performed at zero temperature, so the pure dipole dephasing rate due to scattering is negligible compared with the population decay rates due to longitudinal optical phonon emission events at low temperature.

In this paper, we consider the triple quantum well interacts with a weak pulsed laser field (with central frequency ω_p and amplitude E_p) that couples transition between states $|0\rangle$ and $|1\rangle$, simultaneously, $|1\rangle \leftrightarrow |2\rangle$ and $|1\rangle \leftrightarrow |3\rangle$ transitions are coupled by a strong control field (with frequency ω_c and amplitude E_c) and a pump field (with frequency ω_b and amplitude E_b), respectively. The schematic of the system interacting with three light fields is showed in Fig. 1(b).

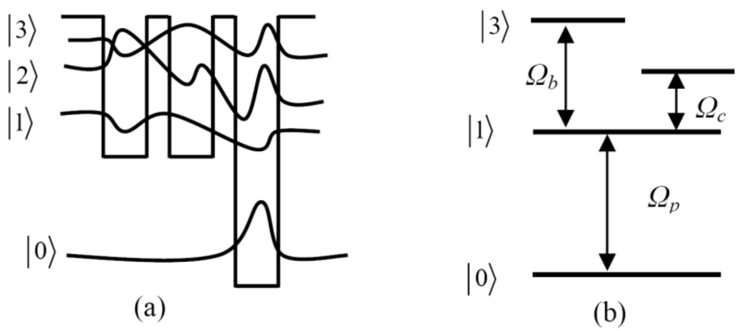

Fig. 1. Band diagram of a triple semiconductor quantum well.

A deep 7.1-nm-thick GaAs well is coupled, on one side, to two shallow 6.8-nm-thick $Al_{0.2}Ga_{0.8}As$ wells by a 2.5-nm-thick $Al_{0.4}Ga_{0.6}As$ barrier. The two shallow wells are separated by a 2.0-nm-thick $Al_{0.4}Ga_{0.8}As$ barrier. Both sides of quantum well contact with 36 nm $Al_{0.4}Ga_{0.6}As$. The electronic wave functions of the ground state of the deep well and the three excited states are shown with respective energies of 52.8 ($|0\rangle$), 197.1 ($|1\rangle$), 206.2 ($|2\rangle$), and 219.4 ($|3\rangle$) meV. (b) the schematic of the system interacting with three light fields.

In the interaction picture, the wave function of the triple semiconductor quantum well can be written in the form (at time t) $|\Psi(t)\rangle = C_0(t)|0\rangle + C_1(t)|1\rangle + C_2(t)|2\rangle + C_3(t)|3\rangle$, and the corresponding time-dependent Schrödinger equation is (we let $\hbar = 1$)

$$\begin{pmatrix} \dot{C}_0(t) & \dot{C}_1(t) & \dot{C}_2(t) & \dot{C}_3(t) \end{pmatrix}^T = -iV_I \begin{pmatrix} C_0(t) & C_1(t) & C_2(t) & C_3(t) \end{pmatrix}^T, \tag{1}$$

where superscript T denotes transpose, and the Hamiltonian V_I describes the four-level system interacting with three light fields. By using the completeness relation $\sum_{k=0}^{3} |k\rangle\langle k| = I$ and considering the effect of decay interference, the matrix form of the Hamiltonian can be written as

$$V_I = \begin{pmatrix} 0 & -\Omega_p^* & 0 & 0 \\ -\Omega_p & -\Delta_p - i\gamma_1/2 & -\Omega_c^* & -\Omega_b^* \\ 0 & -\Omega_c & -\Delta_c - \Delta_p - i\gamma_2/2 & ip_{23}\sqrt{\gamma_2\gamma_3}/2 \\ 0 & -\Omega_b & -ip_{23}\sqrt{\gamma_2\gamma_3}/2 & -\Delta_b - \Delta_p - i\gamma_3/2 \end{pmatrix}, \tag{2}$$

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where $\Omega_p = D_{10}E_p / 2\hbar$, $\Omega_c = D_{21}E_c / 2\hbar$, and $\Omega_b = D_{31}E_b / 2\hbar$ are the half Rabi frequency for the intersubband transitions $|0\rangle \leftrightarrow |1\rangle$, $|1\rangle \leftrightarrow |2\rangle$ and $|1\rangle \leftrightarrow |3\rangle$, respectively. Δ_p, Δ_b, and Δ_c are the detunings of the pulsed light, the pump light and the control field from their respective optical transitions. The parameter p_{23} stands for the alignment of two decay emission dipole matrix elements and is defined as $p_{23} = \vec{D}_{31} \bullet \vec{D}_{21} / (|\vec{D}_{31}||\vec{D}_{21}|) = \cos\theta$ with θ being the angle between the two dipole elements. In experiment, the decay interference requires the levels $|2\rangle$ and $|3\rangle$ are close in our system, that is, they are two close-lying levels, and the corresponding dipole matrix elements are not orthogonal. Theses rigorous conditions are rarely met in real atoms. In the quantum well, energy spacing between the two higher excited states are easily adjusted by changing the structure of well. Furthermore, in order to obtain significant decay interference, the system satisfies the restriction that each field acts only on one transition. In our paper, we assume choice of parameter p is theoretically unrestricted ($p \in [0,1]$), and our aim is investigating the influence of decay interference on the propagation of a pulsed light.

In the slowly varying envelope approximation, Maxwell's equation that denotes the dynamic response of the pulsed light is described by $\partial E_p / \partial t + c\partial E / \partial z = iN\omega_p D_{01} C_1 C_0^*$. According to $\Omega_p = D_{10}E_p / (2\hbar)$, the Maxwell's equation is rewritten as

$$\frac{\partial \Omega_p}{\partial z} + \frac{1}{c}\frac{\partial \Omega_p}{\partial t} = i\kappa C_1 C_0^*, \tag{3}$$

where $\kappa = N\omega_p |D_{10}|^2 / (2\hbar c)$, N is the electron density in the coupled quantum well sample.

We now assume that the pulsed light is weak enough so that we can perform a perturbation expansion of the amplitude, so the first order of the pulsed light Ω_p and the amplitudes $C_{1,2,3}$ are retained [17]. In addition, we assume that the system of quantum well is initially in the state $|0\rangle$ ($C_0 \approx 1$). Under the condition of the weak field approximation, we carry out Fourier transformations $C_{1,2,3}(t) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} \alpha_{1,2,3}(\omega) e^{-i\omega t} d\omega$, with the Fourier transformation variable ω for Eq. (1) and $\Omega_p(t) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} \Lambda_p(\omega) e^{-i\omega t} d\omega$ for Eq. (3), we obtain

$$\alpha_1 = \frac{(p_{23}^2\gamma_2\gamma_3/4 - (\Delta_p + \Delta_b + i\omega + i\gamma_3/2)(\Delta_p + \Delta_c + i\omega + i\gamma_2/2))\Lambda_p}{\begin{pmatrix} (-\Delta_p - i\omega - i\gamma_1/2)(p_{23}^2\gamma_2\gamma_3/4 - (\Delta_p + \Delta_b + i\omega + i\gamma_3/2)(\Delta_p + \Delta_c + i\omega + i\gamma_2/2)) - \\ |\Omega_c|^2(\Delta_p + \Delta_b + i\omega + i\gamma_3/2) + (\Omega_b^*\Omega_c - \Omega_c^*\Omega_b)p_{23}\sqrt{\gamma_2\gamma_3}/2i - |\Omega_b|^2(\Delta_p + \Delta_c + i\omega + i\gamma_2/2) \end{pmatrix}}, \tag{4}$$

$$\frac{\partial \Lambda_p}{\partial z} - i\frac{\omega}{c}\Lambda_p = i\kappa\alpha_1. \tag{5}$$

Substituting Eq. (4) into Eq. (5), we then get $\partial\Lambda_p / \partial z = iK(\omega)\Lambda_p$, where the frequency-dependent propagation factor $K(\omega)$ is given as $K(\omega) = \omega / c - \kappa\alpha_1 / \Lambda_p$. In order to obtain the properties of the propagation for the pulsed light, the propagation factor is expected into a Taylor series as a function of the angular frequency ω, so we obtain

$$K(\omega) = K(0) + K'(0)\omega + K''(0)\omega^2 / 2 + O(\omega^3),$$

where the real part of $K(0)$ denotes the phase shift per unit length, the imaginary part of $K(0)$ stands for energy absorption, $\mathrm{Re}(1/K'(0))$ is the group velocity v_g, $K''(0)$ is called as the

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group velocity dispersion which contributes to the input pulsed shape change and additional loss of the pulsed intensity, and $O(\omega^3)$ are the terms of high order.

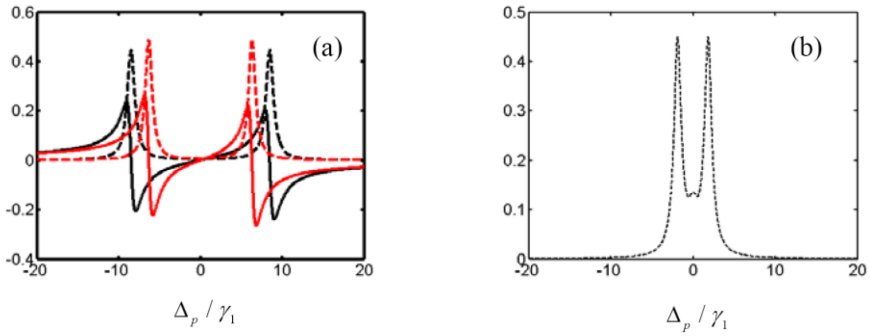

Fig. 2. Curves of absorption (dashed line) and dispersion (solid line) of pulsed light. Physical parameters: $\kappa = 0.5\gamma_1$, $\gamma_2 = \gamma_1$, $\gamma_3 = 1.5\gamma_1$, $\Omega_c = 6\gamma_1$, $\Delta_c = \Delta_b = 0$. For (a), decay interference $p = 0$, $\Omega_b = 6\gamma_1$ is for black line, and $\Omega_b = 2\gamma_1$ is for red line; For (b), $p = 0.96$ and $\Omega_b = 2\gamma_1$.

Now, based on the various physical parameters of the system, we investigate the probe absorption and dispersion and propagation of the pulsed light. We first consider influences of atomic coherence induced by external fields. We choose physical parameters $\Delta_b = \Delta_c = 0$, that is, the system is in the two-photon resonance. The curves of the probe absorption and dispersion are shown in Fig. 2(a). From this figure, we find the system shows one transparent window for the probe field, that is, EIT occurs, which is similar to phenomena produced in cascade-type three-level atomic system [18]. In addition, if the intensity of the control field is kept unchangeable and intensity of the pump field is changed, the width of transparent window changes: decreasing the intensity of the pump field, the window becomes narrow (see black dashed line and red dashed line in Fig. 2(a)). Under the condition of two-photon resonance, if we consider the decay interference simultaneously, where we choose strong effect of decay interference and let $p = 0.96$, the plot of absorption is shown in Fig. 2(b). This figure shows transparent window disappears. In the place of zero detuning, a weak absorption peak appears, which can be explained as follows: decay interference destroys the atomic coherence induced by external fields and destructive interference of the system becomes weak, so the medium does not become transparent.

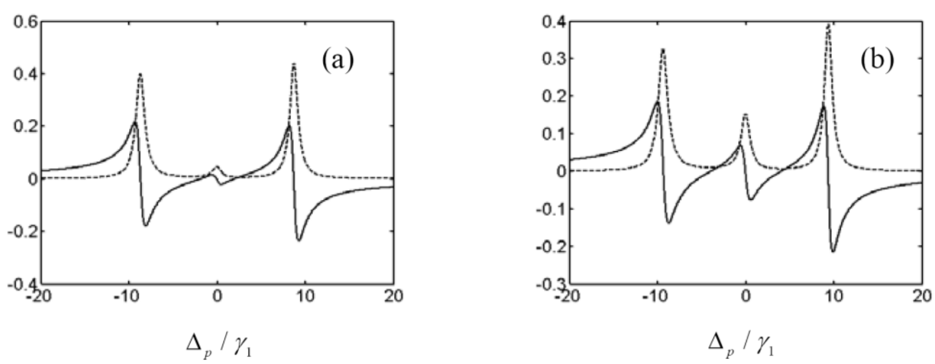

Fig. 3. Curves of absorption (dashed line) and dispersion (solid line) of pulsed light. $\kappa = 0.5\gamma_1$, $\gamma_2 = \gamma_1$, $\gamma_3 = 1.5\gamma_1$, $\Omega_c = \Omega_b = 6\gamma_1$, $p = 0$. For (a), $\Delta_b = 2\gamma_1 = -\Delta_c$; For (b), $\Delta_b = 4\gamma_1 = -\Delta_c$.

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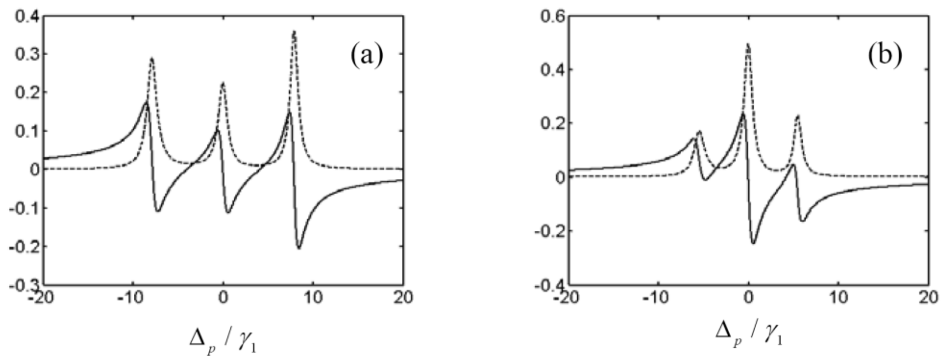

Fig. 4. Curves of absorption (dashed line) and dispersion (solid line) of pulsed light. The parameters are same as Fig. 3(b) but with $p = 0.6$ for (a) and $p = 0.96$ for (b).

Next, we consider the case where $\Delta_b = -\Delta_c \neq 0$ and the control field and pump field have same Rabi frequency. Firstly, the effect of atomic interference based on induction of external fields is considered. The curves of absorption and dispersion versus dimensionless detuning Δ_p / γ_1 may be plotted as shown in Figs. 3(a) and 3(b). The two figures show that two EIT windows occur. With the increase of detuning Δ_b and $-\Delta_c$, the central peak of absorption become higher, and both sides of absorption peaks become lower. In this case, the occurrences of two EIT windows result from the quantum interference effect induced by the control field and pump field. Similar phenomena can also occur in the four-level atomic system [19,20]. If we consider the effect of decay interference, the curve of probe absorption obviously changes (see Figs. 4(a) and 4(b)), where the parameter p which denotes decay interference has different value without changing other parameters noted in Fig. 3(b). Comparing Fig. 4 with Fig. 3(b), we can find locations of transparent windows move significantly and the width of windows narrows when the decay interference intensifies from $p = 0$ to $p = 0.96$, and it is also to be seen the central absorption peak increases obviously and both sides of absorption are inhibited significantly. In fact, in the case of $p = 0.96$ which means strong decay interference, the minimum value of curve of absorption approaches zero and do not reach zero (see Fig. 4(b)), that is, strong decay interference affects destructive interference produced by external fields, which makes weak absorption appear.

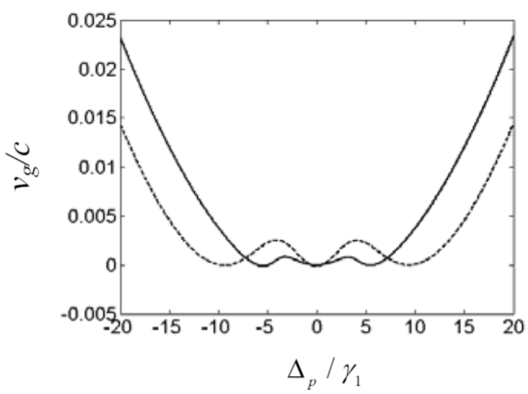

Fig. 5. The plot of the ratio v_g/c as a function of variable Δ_p / γ_1. $p = 0$ for dashed line, $p = 0.96$ for solid line, and other parameters are shown in text.

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In this quantum coherence medium, if we choose $\gamma_1 = 1.0\times 10^5 s^{-1}$, $\kappa = 0.5\gamma_1$, $\gamma_2 = \gamma_1$, $\gamma_3 = 1.5\gamma_1$, $\Omega_c = \Omega_b = 6\gamma_1$, $\Delta_b = 4\gamma_1 = -\Delta_c$, for different values of decay interference *p*, the ratio v_g / c of group velocity of pulsed light to the velocity of light is plotted in Fig. 5, where the dashed curve means that decay interference is not considered ($p = 0$), and the influence of decay interference on the group velocity is shown by solid curve ($p = 0.96$). We find, in the places of absorption peaks ($\Delta_p / \gamma_1 = 0, \pm 5$ for solid line, $\Delta_p / \gamma_1 = 0, \pm 10$ for dashed line), the pulsed light propagates in the coherent medium with minimum velocity that is far less than the velocity of light ($v_g / c \sim 10^{-4}$). In the locations of transparent windows ($\Delta_p / \gamma_1 \sim \pm 2.5$ for solid line, $\Delta_p / \gamma_1 \sim \pm 5$ for dashed line), we find values of v_g / c of solid line are less than ones of dashed line, which means we can get slower light in transparent medium if we consider effect of decay interference.

In summary, we have investigated and analyzed the influence of atomic coherence induced by external fields and decay interference on the probe absorption and dispersion in a triple semiconductor quantum well structure. One EIT window or two EIT windows can be obtained by changing parameters of external fields. Strong decay interference can affect atomic coherence and weakens destructive interference due to atomic coherence, and ultimately transparent windows disappear or weaken. In addition, a new scheme to achieve slow propagation of the pulsed field has been proposed. Compared with the case in atomic system, semiconductor quantum well may easily be designed and integrated, so it has more practical value. Slow light proposed in present work may lead to important applications such high fidelity optical delay lines and optical buffers.

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