Phase tunable slow light in double quantum dot molecules

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Phase-controlled slow and fast light in double coupled quantum dot molecules (QDMs) is researched theoretically. The system absorption and slow factor are 2π-period phase-dependent. It is very effective to switch between slow-light and fast-light state by changing the frequency detuning, Rabi frequency and relative phase of the three coupling lasers. Due to the QDMs' more flexible and adjustable properties than conventional atomic ones, such a system may be more practical. This work may be used to design tunable optical buffer or other solid-state optical devices.

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1. Introduction

In the past decades, variable researches have been carried on slow light ($v_g < c$) and fast light ($v_g > c$ or v_g is negative) in atomic vapors and solid-state materials [1-14] theoretically and experimentally, for its potential applications such as optical buffer, switching etc. in the optical communication and quantum information processing. For instance, electromagnetically induced transparency [EIT] has been used to reduce group velocity down to 17 m/s in an ultracold sodium vapour experimentally [3]. Safavi-Naeini et al. [6] reported fast light with a 1.4 μs signal advance in a nanoscale optomechanical crystal device. Clark et al. [7] observed an advancement of the quantum fluctuations in a fast-light medium. Akram et al. [8] reported tunable slow and fast light in a hybrid optomechanical system. Arrieta-Yanez et al. [41] reviewed the slow and fast light based on coherent population oscillations in optical fibers doped with erbium ions.

In the same time, slow and fast light in quantum wells and dots [15-37] also attaches great attention for their special properties such as strong nonlinear, large electric dipole moments, fabricability and compatibility in devices. For example, Ma et al. [18] observed a transient EIT in GaAs/AlGaAs multiple quantum wells. Borges et al. [23] reported slow light in QDMs based on tunneling induced transparency. Azizi et al. [33] investigated EIT in a quantum pseudo-dot with Rashba spin–orbit interaction affected by external magnetic field.

Recently, Xiao et al. [42] reviewed the development of active metamaterials and metadevices including QDs ranging from microwave to visible wavelengths. For QD's subwavelength scale, it is effective for active tuning and provides flat, high-efficiency alternatives to conventional optical systems based on bulky components. Motivated by this and the previous studies, in this paper, we investigate the slow-and-fast light in a double coupled QDMs system. The system optical absorption and slow factor of the probe pulse are phase-controlled easily and can be adjusted by the other system parameters. What is more, due to the fabricability of the QDMs, the results can be extended to the optical communication.

2. Model and theory

A system containing two different-in-size QDs with four energy levels [38,39] is considered in this paper showing in Fig. 1a. It can be produced by the molecules beam epitaxy. The energy levels can be calculated by solving the effective-mass Schrödinger equations. The transition can be carefully designed to have energy for the required system by choosing suitable parameters. The four energy levels can be chosen as $E_1 = 0.8365\text{eV}$, $E_2 = 1.0036\text{eV}$, $E_3 = 0.8537\text{eV}$, $E_4 = 1.066\text{eV}$ [38,39]. A probe laser (Rabi frequency Ω_p and frequency ω_p) is applied on the transition $|1\rangle \leftrightarrow |2\rangle$. Three coupling laser

(Rabi frequency Ω_c, Ω_d, Ω_g and frequency $\omega_c, \omega_d, \omega_g$) is applied in the system showing in Fig. 1b. And we denote such four laser fields with alphabets p, c, d and g in the following.

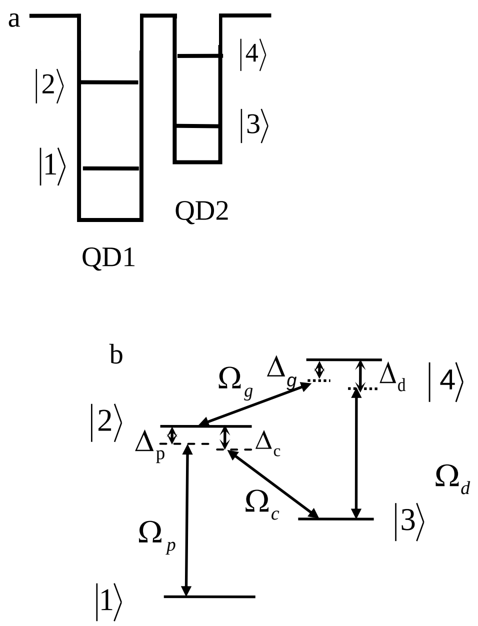


Fig. 1. Diagrams of the QDs system and the applied laser fields. (a) Two coupled QDs system with four energy levels. (b) QDs system interacting with four laser fields

In the interaction picture, the system Hamiltonian can be read as (taking $\hbar=1$),

$$H_{int}^{I} = \begin{pmatrix} 0 & -\Omega_p & 0 & 0 \\ -\Omega_p & \Delta_p & -\Omega_c & -\Omega_g e^{i\varphi} \\ 0 & -\Omega_c & \Delta_p + \Delta_c & -\Omega_d \\ 0 & -\Omega_g e^{-i\varphi} & -\Omega_d & \Delta_p + \Delta_c + \Delta_d \end{pmatrix}, \quad (1)$$

Using the standard approach, the Schrodinger equation can be solved [35]. We can obtain,

$$-i\frac{d}{dt}a_1 = \Omega_p a_2 \quad , \quad (2a)$$

$$-i\frac{d}{dt}a_2 = \Gamma_2 a_2 + \Omega_p a_1 + \Omega_c a_3 + \Omega_g e^{i\varphi} a_4 \quad , \quad (2b)$$

$$-i\frac{d}{dt}a_3 = \Gamma_3 a_3 + \Omega_c a_2 + \Omega_d a_4 \quad , \quad (2c)$$

$$-i\frac{d}{dt}a_4 = \Gamma_4 a_4 + \Omega_g e^{-i\varphi} a_2 + \Omega_d a_3 \quad , \quad (2d)$$

where $\Gamma_2 = \Delta_p + i\gamma_2$, $\Gamma_3 = \Delta_p + \Delta_c + i\gamma_3$, $\Gamma_4 = \Delta_p + \Delta_c + \Delta_d + i\gamma_4$. And $\Delta_c = \omega_c - \omega_{23}$, $\Delta_d = \omega_d - \omega_{43}$, $\Delta_g = \omega_g - \omega_{42}$, $\Delta_p = \omega_p - \omega_{21}$ are the frequency detuning showing in Fig. 1(b) with ω_{ij} being the transition frequency between the state $|i\rangle$ and $|j\rangle$. $a_j (j = 1-4)$ is the probability of the state $|j\rangle$. $\gamma_i (i = 2,3,4)$ is the corresponding total population dephasing and decay rate. φ is the relative phase of the laser field c, d and g which can be seen in Fig. 1(b). $\Omega_{p(c,d,g)} = \mu E_{p(c,d,g)}$ is the Rabi frequency of the laser field, with assuming $\mu = \mu_{21} = \mu_{23} = \mu_{42} = \mu_{43}$ simply and μ_{ij} being the electric dipole moment of transition between $|i\rangle$ and $|j\rangle$. $E_{p(c,d,g)}$ is the electric field amplitude. The relation $\Delta_d = \Delta_c + \Delta_g$ is satisfied.

In the steady state, solving Eq. (1) with the weak field approximation ($|a_1|^2 = 1$), we can get

$$\rho_{21} = a_2 a_1^* = \Omega_p A/B \quad , \quad (3)$$

where, $A = \Omega_d^2 - \Gamma_3\Gamma_4$,

$$B = \Gamma_2\Gamma_3\Gamma_4 - \Gamma_2\Omega_d^2 - \Gamma_3\Omega_g^2 - \Gamma_4\Omega_c^2 + \Omega_c\Omega_d\Omega_g(e^{i\varphi} + e^{-i\varphi}).$$

The linear susceptibility can be written as [30]

$$\chi^{(1)} = \frac{N\mu^2}{\hbar\varepsilon_0\Omega_p}\rho_{21} = \frac{N\mu^2}{\hbar\varepsilon_0}\chi \quad , \quad (4)$$

$$\chi = \frac{A}{B} \quad , \tag{5}$$

where N is the electron density in the QDs. The slow factor can be defined as

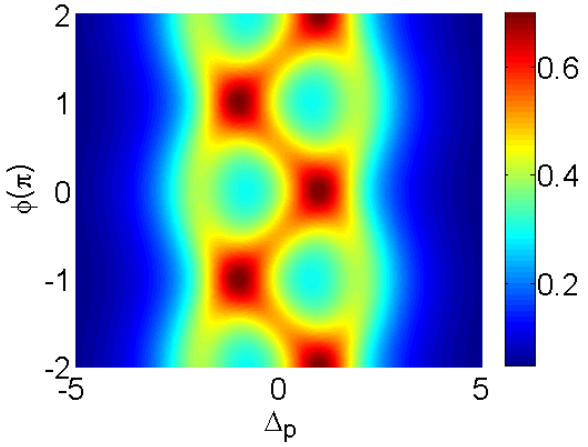
$$S = \frac{c}{v_g} = 1 + \mathrm{Re}\chi^{(1)} + \omega \frac{d}{d\omega} \mathrm{Re}\chi^{(1)} \quad , \tag{6}$$

where v_g is the group velocity of the probe laser. c is the light speed in vacuum.

3. Numerical results

In the following, the slow and fast light in our system is theoretically studied based on Eq. (4-6). It is well known that the group velocity $v_g < c$ is slow light in the normal dispersion regime (i.e. $\partial(\mathrm{Re}\chi) / \partial\omega > 0$), and the group velocity $v_g > c$ is fast light in the anomalous dispersion regime (i.e. $\partial(\mathrm{Re}\chi) / \partial\omega < 0$). The common parameters are $N = 1\times10^{22} m^{-3}$, $\mu = 4.8\times10^{-28}$ Cm [30]. We adopt $\gamma_2 = \gamma_3 = \gamma_4 = \gamma = 1meV$ simply firstly.

First, in order to reveal the optical properties of the system, we plot the probe absorption $\mathrm{Im}\chi$ for the relative phase φ and the probing field detuning Δ_p in Fig. 2a. It is found that the system absorption is 2π -period phase-dependent. To see and compare clearly, we also plot detailed $\mathrm{Im}\chi$ for $\varphi = 0$, $\pi/2$ and π with different probe laser frequency detuning Δ_p in Fig. 2b. We can find the transparency window can be monitored by the relative phase φ .



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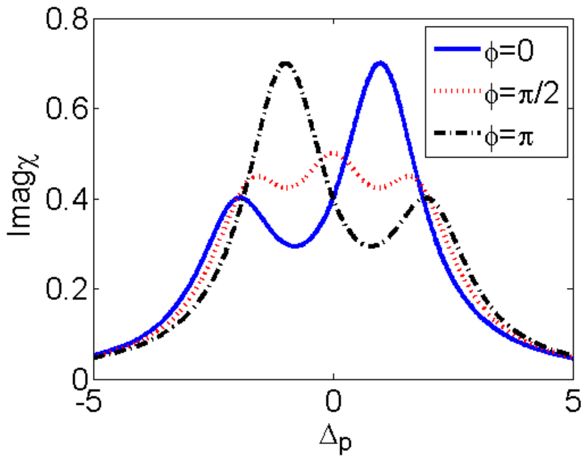

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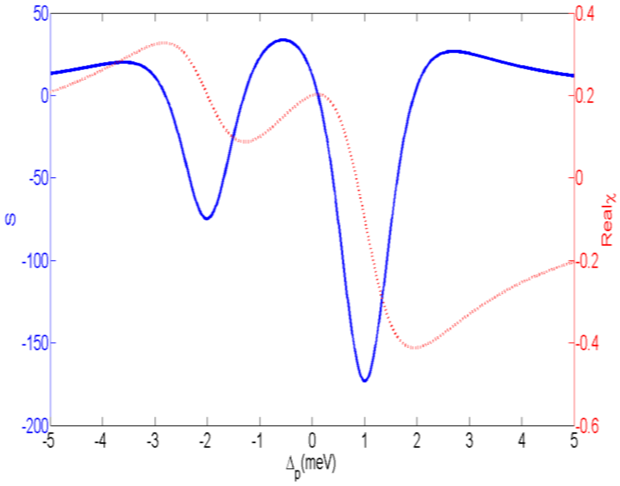
Fig. 2. (a) Density plot of the probe absorption $\mathrm{Im}\chi$ *for the relative phase* φ *and the probing field detuning* Δ_p *. (b) Detailed* $\mathrm{Im}\chi$ *for* $\varphi = 0$, $\pi/2$ *and* π *. The other parameters are,* $\Omega_c = \Omega_d = \Omega_g = 1meV$, $\Delta_c = \Delta_d = 0$ *(color online)*

Second, we plot S and $\mathrm{Re}\chi$ for the probing field detuning Δ_p with $\varphi = 0$ in Fig. 3a. It is clear the relation between S and $\mathrm{Re}\chi$ satisfies Eq. (6). We also plot the density of the slow factor S for the relative phase φ and the probing field detuning Δ_p in Fig. 3b. Obviously, the slow factor S is 2π -period phase-dependent. To see clearly, we plot the slow factor S for the relative phase φ with $\Delta_p = 0$. The maximum slow factor is 11.5 at $\varphi = k\pi(k = 0, \pm1, \pm2, \cdots)$, and minimum slow factor is -67 at $\varphi = k\pi + \pi/2 (k = 0, \pm1, \pm2, \cdots)$. What is more, from Fig. 2b and Fig. 3a, we can find that the transparency window (absorption peaks) with negligible (strong) absorption is related to the normal (anomalous) dispersion regimes for φ=0 .



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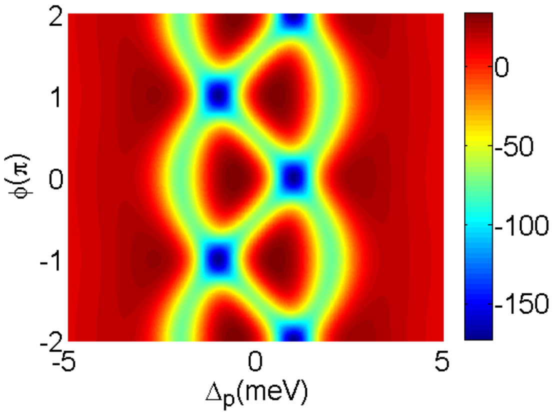

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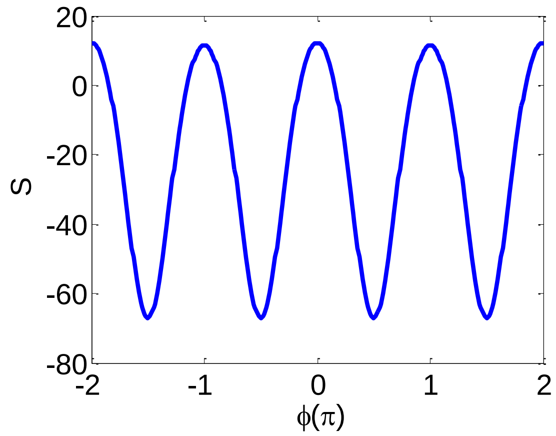

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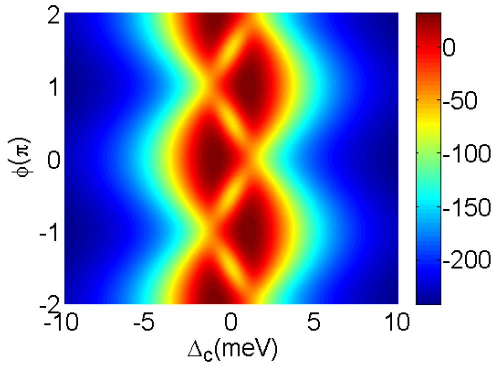
Fig. 3. (a) Plots of S *and* Reχ *for the probing field detuning* Δ_p *with* $\varphi = 0$. *(b) Density plot of the slow factor* S *for the relative phase* φ *and the probing field detuning* Δ_p. *(c) Plots of* S *for the relative phase* φ *with* $\Delta_p = 0$. *The other parameters are,* $\Omega_c = \Omega_d = \Omega_g = 1\text{meV}$, $\Delta_c = \Delta_d = 0$ *(color online)*



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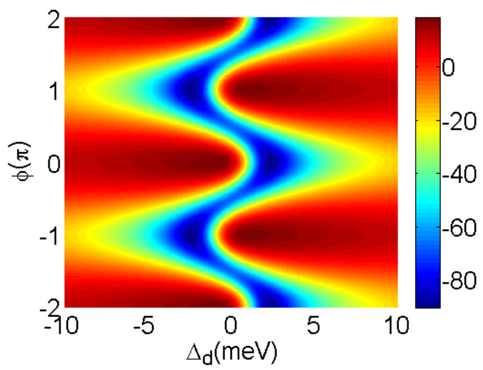
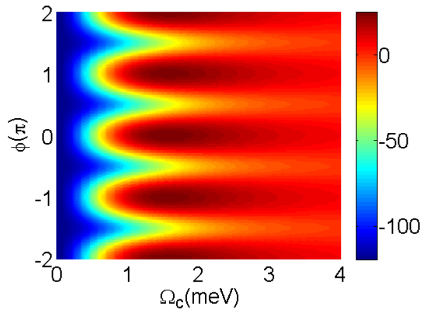


b

Fig. 4. (a) Density plot of the slow factor S *for the relative phase* φ *and the coupling-c field detuning* Δ_c. $\Delta_p = \Delta_d = 0$. *(b) Density plot of the slow factor* S *for the relative phase* φ *and the coupling-d field detuning* Δ_d. $\Delta_p = \Delta_c = 0$. *The other parameters are,* $\Omega_c = \Omega_d = \Omega_g = 1\text{meV}$ *(color online)*

Third, we plot the density of the slow factor S for the relative phase φ and the coupling-c field detuning Δ_c in Fig. 4a. We can mainly find slow light for $-1\text{meV} < \Delta_c < 1\text{meV}$. When the absolute value of Δ_c is more than 1meV, it is in the fast-light area. We also plot the density of the slow factor S for the relative phase φ and the coupling-d field detuning Δ_d in Fig. 4b. We can find the maximum (minimum) slow factor is at $\Delta_d = \pm 2$ meV ($\Delta_d = \pm 1$ meV) for $\phi = k\pi (k = 0, \pm1, \pm2, \cdots)$.



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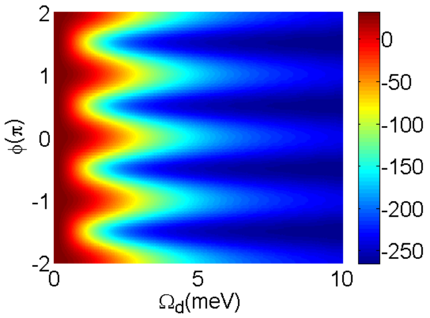

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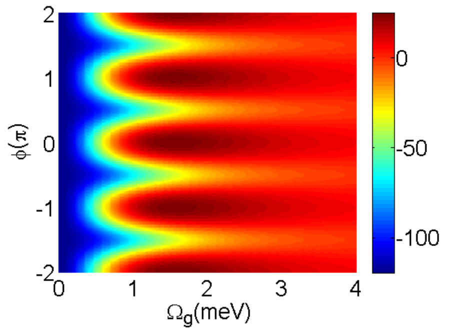

c

Fig. 5. (a)Density plot of the slow factor S *for the relative phase* φ *and the coupling-c field* Ω_c. $\Omega_d = \Omega_g = 1\text{meV}$. *(b)Density plot of the slow factor* S *for the relative phase* φ *and the coupling-d field* Ω_d. $\Omega_c = \Omega_g = 1\text{meV}$ *.(c)Density plot of the slow factor* S *for the relative phase* φ *and the coupling-g field* Ω_g. $\Omega_c = \Omega_d = 1\text{meV}$ *. The other parameters are,* $\Delta_p = \Delta_c = \Delta_d = \Delta_g = 0$ *(color online)*

Fourth, we plot density of the slow factor S for the relative phase φ and the coupling-c(d,g) field in Fig. 5a(b,c). We can find the coupling-c and coupling-g field have a similar influence on the slow factor. When $\Omega_{c(g)}$ is less than 1meV, it is in the fast-light area. When $\Omega_{c(g)}$ is about 1.5meV, we can get the maximum slow factor $S = 24$ for $\varphi = k\pi (k = 0, \pm 1, \pm 2, \cdots)$. However, it is contrary for coupling-d field. When Ω_d is less than 1meV, it is in the slow-light area. When Ω_d is more than 1meV, it is in the fast-light area.

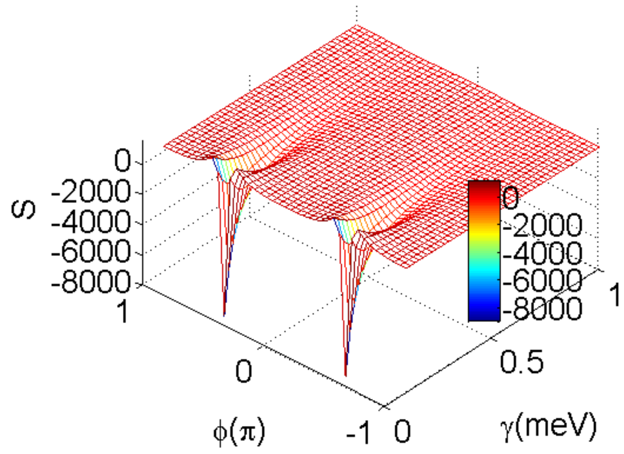

Fig. 6. Density plot of the slow factor S *for the relative phase* φ *and the decaying rate* γ *. The other parameters are,*

$$\Omega_c = \Omega_d = \Omega_g = 1\text{meV} .$$

$$\Delta_p = \Delta_c = \Delta_d = \Delta_g = 0 \textit{ (color online)}$$

Finally, we plot the density of the slow factor S for the relative phase φ and the decaying rate γ in Fig. 6 for the decaying rate varies with the different temperature [40]. We can find at low temperature, the slow factor changes drastically from -6000 to 1000 for $\gamma = 0.1\text{meV}$ near $\varphi = \pm\pi/2$ by monitoring the relative phase.

4. Conclusions

In this paper, the slow-and-fast light in the double coupled QDMs has been investigated. The slow factor, normal and anomalous dispersion of the system can be controlled by the relative phase of the three coupling lasers along with the frequency detunning and Rabi frequency. Our calculations may provide a guideline to optimize the tunable optical buffer in the optical communication, which is much more practical than those in atomic system due to the fabricability of QDs.

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