Slow light propagation without absorption based on intersubband transitions in a semiconductor quantum well*

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When semiconductor quantum wells (SQWs) interact with lasers, the group velocity of the low-intensity light pulse is studied theoretically. It is shown that by adjusting the parameters, slow light propagation of the probe field can be exhibited in such a system. Meanwhile, the probe absorption-gain spectra can be changed from absorption to zero, i.e., electromagnetically induced transparency (EIT). It is easy to observe the light propagation experimentally, and it leads to potential applications in many fields of solid-state quantum information, for example, optical switching, detection and quantum computing.
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With the intersubband transitions in semiconductor quantum wells (SQWs), many significant researches on quantum coherence and interference phenomena[1,2] have been done. As we all know, SQWs have some properties similar to atomic vapors. Compared with atomic vapors, their dipole moments, transition energy and symmetry can be engineered as desired[3,4]. For their potential applications in optoelectronics and solid-state quantum information region, a number of fascinating coherence-introduced effects have been reported[5,6], such as tunneling-induced transparency[7], lasing without inversion[8,9], enhanced index of refraction without absorption[10] and coherent population trapping[11]. Based on these effects, some extremely useful devices, for example, ultrafast optical switches[12,13] and quantum switches[14], can be obtained.

The group velocity of the probe field can be slowed down to 17 m/s in Bose-Einstein condensate (BEC)[15]. Also, the slow light phenomena were reported in SQWs[16,17]. In asymmetric double quantum wells, via tunable Fano interference[5], Wu et al reported an ultrafast all-optical switching. Prineas et al[18] showed the tunable slow light in Bragg-spaced quantum wells. Frogley et al[19] reported the light as slow as $c/40$ over the spectral range where the optical gain appears in semiconductor nanostructures. Our group also investigated these phenomena in semiconductor heterostructures[20,21].

In this paper, with three-subband system, we theoretically study the group velocity of the probe field in a quantum well (QW) structure. Here, the QW medium provides a highly tunable quantum system. It is shown that in the almost zero absorption or electromagnetically induced transparency (EIT) region, the group velocity of the probe field is less than the light speed in vacuum c, i.e., slow light propagation appears. This kind of properties may lead to potential applications in many fields of optical signal processing in solid-state quantum information region.

As shown in Fig.1, a quantum well structure with three energy levels is considered, which forms the cascade configuration. This model has been considered in Refs.[19] and [22], where alternating current (ac) Stark splitting and gain

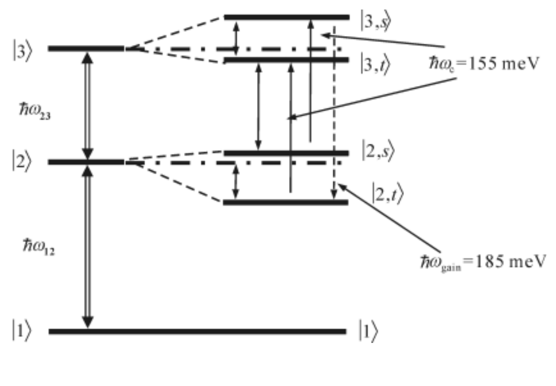

Fig.1 Schematic diagram of the three-level cascade electronic system synthesized in an SQW

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without inversion are investigated. It allows the electronic transition of $|1\rangle \leftrightarrow |2\rangle$ to be probed via the extra absorption features, which is produced in a distinctly different spectral region.

Utilizing the rotating-wave approximation and the electric-dipole approximation, the equations of motion for the probability amplitude of the electronic wave functions can be employed in the interaction as

$$\frac{\partial\rho_{11}}{\partial t}=\gamma_2\rho_{22}+\mathrm{i}\,\Omega_{\mathrm{c}}(\rho_{12}-\rho_{21}),$$

$$\frac{\partial\rho_{22}}{\partial t}=-\gamma_2\rho_{22}+\gamma_3\rho_{33}-\mathrm{i}\,\Omega_{\mathrm{c}}(\rho_{12}-\rho_{21})+\mathrm{i}\,\Omega_{\mathrm{p}}(\rho_{23}-\rho_{32}),$$

$$\frac{\partial\rho_{33}}{\partial t}=-\gamma_3\rho_{33}-\mathrm{i}\,\Omega_{\mathrm{p}}(\rho_{23}-\rho_{32}),$$

$$\frac{\partial\rho_{12}}{\partial t}=(\mathrm{i}\,\Delta_1-\gamma_{12})\rho_{12}-\mathrm{i}\,\Omega_{\mathrm{c}}(\rho_{22}-\rho_{11})+\mathrm{i}\,\Omega_{\mathrm{p}}\rho_{13},$$

$$\frac{\partial\rho_{13}}{\partial t}=(\mathrm{i}\,\Delta_2-\gamma_{13})\rho_{13}-\mathrm{i}\,\Omega_{\mathrm{c}}\rho_{23}+\mathrm{i}\,\Omega_{\mathrm{p}}\rho_{12},$$

$$\frac{\partial\rho_{23}}{\partial t}=[\mathrm{i}(\Delta_1+\Delta_2)-\gamma_{23}]\rho_{23}-\mathrm{i}\,\Omega_{\mathrm{p}}(\rho_{33}-\rho_{22})-\mathrm{i}\,\Omega_{\mathrm{c}}\rho_{13}, \qquad (1)$$

where $\Omega_{\mathrm{c(p)}}$ is the Rabi frequency of the coupling (probe) field. The detuning parameters are defined as $\Delta_1=E_2-E_1-\hbar\omega_{\mathrm{c}}$ and $\Delta_2=E_3-E_2-\hbar\omega_{\mathrm{p}}$. γ_2 and γ_3 are the population decays. Here, $\gamma_{12}=\gamma_2+\gamma_{12}^{\mathrm{dph}}$, $\gamma_{23}=\gamma_2+\gamma_3+\gamma_{23}^{\mathrm{dph}}$, and $\gamma_{13}=\gamma_3+\gamma_{31}^{\mathrm{dph}}$, where $\gamma_{i,j}^{\mathrm{dph}}$ is the sum of the elastic interface roughness scattering and the quasielastic acoustic phonon scattering.

For the purpose of designing and exploiting coherent optical effects, QW can be thought as artificial atoms. Here, the intensity of the fields can produce a variety of effects on the quantum coherence. In Fig.2, quantum coherence effects for different Rabi frequencies of the driving field are shown. The correlated parameters are the same as those in Ref.[23]. In our notation, when $\mathrm{Im}(\rho_{23})>0$, the probe field is absorbed. On the contrary, it appears gain. It is shown that according to Fig.2, when the intensity of the coupling field is varied, the system experiences anomalous dispersion with absorption and normal dispersion without absorption.

As shown in Fig.2(a), when $\Omega_{\mathrm{c}}=3$ meV, there is only one peak for the probe field. Meanwhile, the corresponding slope of $\mathrm{Re}(\rho_{23})$ is negative around $\Delta_2=0$, which is anomalous dispersion. In Fig.2(b), increasing Ω_{c} to 5 meV, there is a dip in the gain-absorption line. At the same time, the corresponding slope of the dispersion is turned from negative to positive. When Ω_{c} increases to 15 meV as shown in Fig.2(c), there is almost no absorption, and the corresponding normal dispersion region is also increased. When $\Omega_{\mathrm{c}}=30$ meV as shown in Fig.2(d), the absorption is nearly zero, and the slope of the dispersion is positive around $\Delta_2=0$. Based on the above discussions, when the intensity of the coupling field is increased,

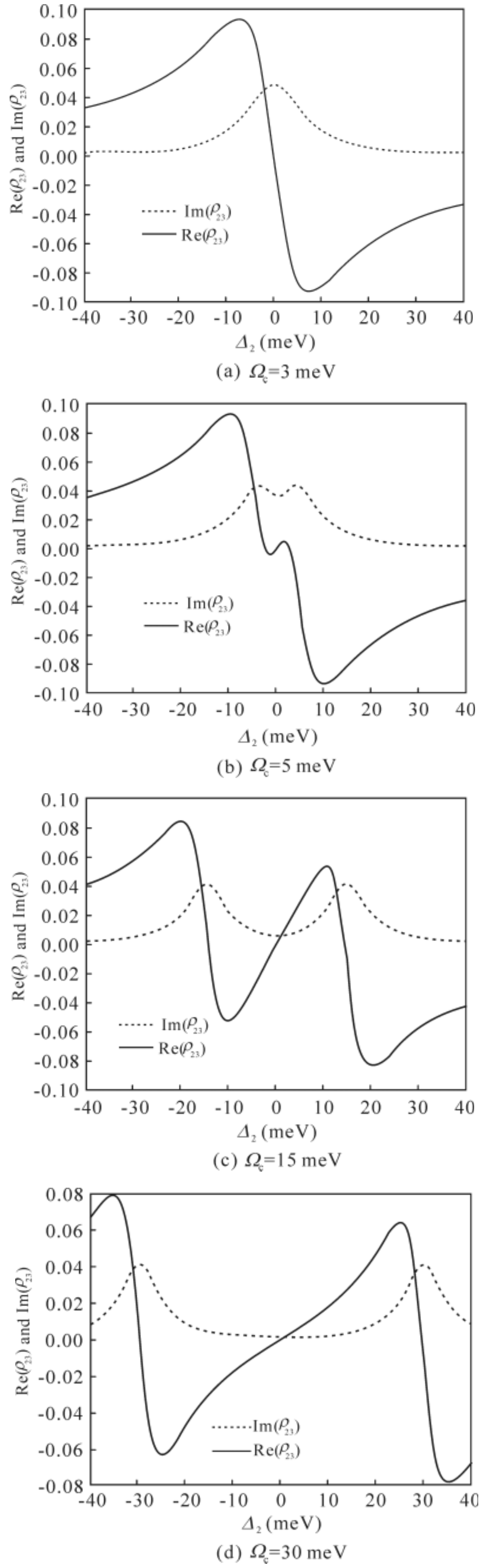

Fig.2 $\mathrm{Im}(\rho_{23})$ and $\mathrm{Re}(\rho_{23})$ of the probe field versus the probe detuning Δ_2 with different coupling fields when $\gamma_2=1.3$ meV, $\gamma_{12}=1.5$ meV, $\gamma_3=\gamma_{13}=0.9$ meV, $\gamma_{23}=2.5$ meV and $\Omega_{\mathrm{p}}=3$ meV

there is the slow light propagation without absorption. Here, with the increasing of the coupling field Ω_c, the variations of the absorption agree well with the results in Ref.[23]. However, the group velocity, i.e., Re(ρ_{23}), is our key which is not considered in Ref.[23].

For further consideration, the group velocity v_g of the probe field is our focus. We investigate the effects of the probe detuning and the coupling field on the group velocity. In a dispersive medium, if the gain-absorption is very small or zero, the group velocity can be written as $v_g = c/n_g \approx c/(n' + \omega\partial n'/\partial\omega)$, where n' is the real part of the refractive index n, c is the light speed in vacuum, and n_g is the group index here. For normal dispersive medium $(\partial n/\partial\omega > 0)$, it leads to the slow light propagating through the medium, i.e., subluminal group velocity. Meanwhile, the complex refractive index n of the medium follows the relation of $n=1+\chi/2$, which is related with ρ_{23} by $\chi=N\mu_{23}\rho_{23}/\varepsilon_0 E_p$, where N is the electron density in the conduction band of quantum well, ε_0 is the permittivity in free space and μ_{23} is the dipole matrix element between $|2\rangle$ and $|3\rangle$.

Fig.3 shows the variation of the group index n_g with the probe detuning Δ_2, where $N=1\times10^{11}$ cm^{-3}, and other parameters are the same as those in Fig.2(d). It is shown that the group index is always positive and larger than 1. That is because the group velocity is slower than the light speed in vacuum of c. Also there exists a dip which corresponds to the maximum group velocity.

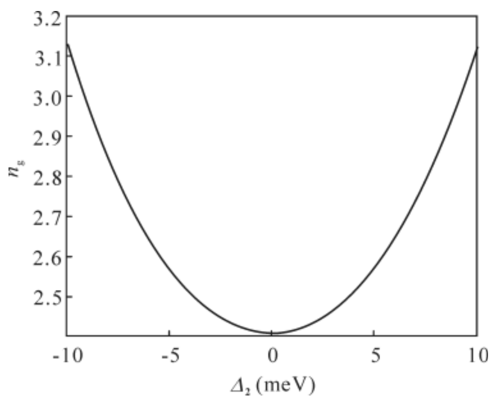

Fig.3 Variation of the group index n_g with the probe detuning Δ_2

The dependence of the group index on the coupling field is shown in Fig.4. On the whole, the group index is decreased with the increase of the coupling field Ω_c, but it is always larger than 1. That is because the group velocity is slower than c. Therefore, we can say that with proper parameters, the subluminal group velocity propagation exists with EIT. This kind of phenomena are similar to the experiment results in Ref.[20] where the group velocity is $c/40$ throughout the spectral region with gain. The result may lead to important applications in quantum communication and quantum computing of solid state materials.

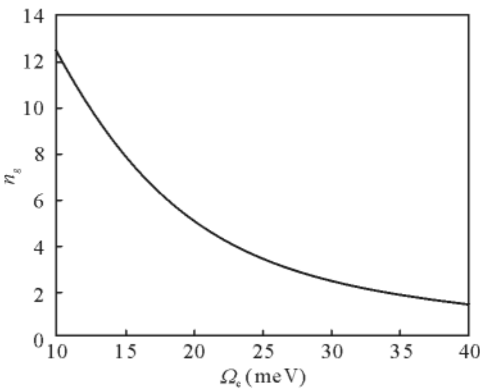

Fig.4 Variation of the group index n_g with the coupling field Ω_c when Δ_2=0 meV, and other parameters are the same as those in Fig.2

In conclusion, we investigate the dispersion and the absorption of a probe field interacting with QWs structure. It is shown that the probe detuning and the Rabi coupling field can affect the optical properties of the QW. With proper fields and probe detuning, the EIT-assisted subluminal phenomenon of the probe field is established in this QW material. It is much more practical than its atomic counterpart because of its adjustable parameters and its flexible design. The phenomena may be helpful for the observation of the group velocity in experiment. More important, it may lead to potential applications in quantum information and quantum computing of SQWs structure.

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