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Intracavity Tunneling Introduced Transparency in Ultrastrong-coupling Regime

Tao Wang, Rui Zhang, Chunxiao Zhou, Xuemei Su
Physics College, Jilin University Changchun 130012, People's Republic of China
Email: suxm@jlu.edu.cn

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ABSTRACT

Intracavity tunneling induced transparency in asymmetric double-quantum wells embedded in a microcavity in the ultrastrong-coupling regime is investigated by the input-output theory developed by Ciuti and Carusotto. In this system a narrow spectra can be realized under anti-resonant terms of the external dissipation. Fano-interference asymmetric line profile is found in the absorption spectra.

Keywords: Ultrastrong Coupling; Spectra Narrowing; Anti-resonant Terms; Fano-interferences

1. Introduction

Intersubband electronic transitions in doped semiconductor quantum wells play an important role in many remarkable devices, such as quantum cascade lasers, quantum-well infrared photodetectors and ultrafast optical modulators [1]. If semiconductor quantum wells in a microcavity were explored by using the intersubband transitions, it can achieve an ultrastrong light-matter coupling regime where vacuum Rabi frequency becomes comparable to the intersubband electronic transitions [2]. In the ultrastrong coupling regime, the usual rotating-wave approximation is not exact enough to explain the experimental data and the antiresonant terms should be considered. The contribution of antiresonant terms can create many new effects such as back-reaction, photon blocked and two-mode squeezed vacuum [3].

Quantum coherence is a fundamental problem in quantum mechanics and has been investigated for a long time in atom physics and optics physics. Strong coupling is necessary for quantum coherence, but we still do not understand what will happen when the coupling strength reaches the ultrastrong-coupling region. The intersubband electronic transition in doped semiconductor quantum wells embedded in a microcavity provide a chance to discuss and test the problem.

A full quantum description of the ultrastrong-coupling regime in doped semiconductor quantum wells microcavity has been developed by Ciuti and Carusotto [4] which can explicitly include the coupling to external dissipation baths including probe photons and injection electrons. The dissipation baths are not only responsible for damping rates but also provide a way of exciting and observing the cavity dynamics. The photonic mode is coupled to the external world mostly because of the finite reflectivity of the cavity mirrors, while the intersubband transition is coupled to other excitations in the semiconductor material-e.g., acoustic and optical phonons and free carriers in levels other than the ones involved in the considered transition. In particular, the coupling to this electronic bath allows one to electrically excite the intersubband transitions and induce electroluminescence. In the theory cavity field and electronic transition are treated as two oscillators . The vacuum Rabi splitting of a collection of oscillators in a single-mode cavity is proportional to the square root of their number. So the control of polariton coupling can be realized through the variation of carrier density.

In this paper we investigate quantum coherence in a multiple asymmetric double-well structure embedded in macrocavities. The cavity mode and the electronic excitations in each quantum well interact strongly in the ultrastrong-coupling regime and the intersubband transitions of each quantum well are coupled by quantum tunneling which can be tuned using bias voltage. Asymmetric semiconductor double quantum well structure has been studied for many interesting phenomena such as lasers without population inversion, tunneling induced transparency (TIT) [5] and optical switching [6].

TIT is a typical interesting quantum coherence phenomena similar as those of the idea of Electromagnetically induced transparency (EIT) [7]. Recent years intracavity EIT has attracted much attentions and has been studied experimentally in the multiatoms-cavity systems [8,9]. It has been shown that intracavity EIT results in an ultra-narrow spectral linewidth which may be used for

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frequency stabilization and high-resolution spectroscopic measurements. When the intracavity dark state is induced by a coupling laser in the cavity and Λ -type atomic system, the cavity transmission spectrum exhibits three peaks: two side-bands associated with the multiatom vacuum Rabi splitting and a narrow central peak representing the cavity dark-state resonance of the two-photon Raman transition.

Ulike atomic systems, semiconductor quantum well embedded in a microcavity is easily use to realize the ultrastrong coupling due to very large subband transition matrix elements [6]. In the asymmetric quantum wells microcavity, the transmission spectrum is similar with the multilevels atom-cavity system but is not symmetric and the narrow peak is not in the central position in the ultrastrong-coupling regime. Intuitively the antiresonant terms reduce the simultaneous creation and annihilation of the cavity photon and the electronic transition so the dark state must be destroyed. However the zero-absorption at resonance is not changed by the aniresonant terms in the ideal condition and can be used to reduce the absorption induced by the aniresonant terms to zero. The results mean that the intracavity TIT still hold even in the ultrastrong-coupling regime.

2. Model

Figure 1 is the energy level diagram of the double quantum wells separated by a thin tunneling barrier. The deep quantum well populates two-dimensional electron gas density (2DEG) in the first subband $|1\rangle$ at low temperatures with gas density. The energy splitting of the energy subband $|2\rangle$ and $|3\rangle$ is caused by resonant tunneling. $\hbar\omega_{12}$, $\hbar\omega_{13}$ are corresponding energies of the two intersubband transition energy from $|1\rangle$ to $|2\rangle$ and $|3\rangle$. If we denote with z the growth direction of the multiple quantum well structure, then the dipole moment of the transition is aligned along z, i.e., $\vec{d}_{12} = d_{12}\hat{\vec{z}}$, $\vec{d}_{13} = d_{13}\hat{\vec{z}}$. The in-plane wave vector $\vec{k}$ is a conserved quantity.

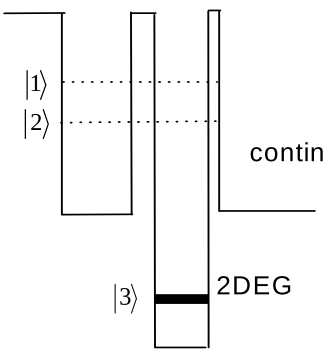

Figure 1. Subband energy level diagram for double quantum wells separated by a thin tunneling barrier. The deep quantum well contains a two-dimensional electron gas in the lowest subband.

The photons mode is chosen to be resonant to the fundamental cavity photon mode, whose frequency dispersion is given by $\omega_{cav,\vec{k}} = \frac{c}{\sqrt{\varepsilon_\infty}}\sqrt{k_z^2 + k^2}$, where ε_∞ is the dielectric constant of the cavity spacer and k_z s the quantized photon wave vector along the growth direction, which depends on the boundary conditions imposed by the specific mirror structures. In the simplest case of mellic mirrors, $k_z = \frac{\pi}{L_{cav}}$, with L_{cav} he cavity thickness.

The Hamiltonian of the present system is

$$\begin{aligned} H &= \sum_{\vec{k}} \hbar\omega_{cav,\vec{k}} a_{\vec{k}}^\dagger a_{\vec{k}} + \sum_{\vec{k}} \hbar\omega_{12} b_{\vec{k}}^\dagger b_{\vec{k}} \\ &+ \sum_{\vec{k}} \hbar\omega_{13} d_{\vec{k}}^\dagger d_{\vec{k}} + \hbar\sum_{\vec{k}} \Big\{ i\Omega_{12,\vec{k}} \left(a_{\vec{k}} b_{\vec{k}}^\dagger - a_{\vec{k}}^\dagger b_{\vec{k}} \right) \\ &+ i\Omega_{13,\vec{k}} \left(a_{\vec{k}} d_{\vec{k}}^\dagger - a_{\vec{k}}^\dagger d_{\vec{k}} \right) + D_{\vec{k}} \left(a_{\vec{k}} a_{\vec{k}}^\dagger + a_{\vec{k}}^\dagger a_{\vec{k}} \right) \Big\} \\ &+ \hbar\sum_{\vec{k}} \Big\{ i\Omega_{12,\vec{k}} \left(a_{\vec{k}} b_{-\vec{k}} - a_{\vec{k}}^\dagger b_{-\vec{k}}^\dagger \right) \\ &+ i\Omega_{13,\vec{k}} \left(a_{\vec{k}} d_{-\vec{k}} - a_{\vec{k}}^\dagger d_{-\vec{k}}^\dagger \right) + D_{\vec{k}} \left(a_{\vec{k}} a_{-\vec{k}} + a_{\vec{k}}^\dagger a_{-\vec{k}}^\dagger \right) \Big\} \end{aligned} \tag{1}$$

The first three terms describe the energy of the cavity mode and the two intersunbband electronic transitions. The fouth term describe the resonant interactions between the cavity photons and the electronic transitions and the fifth terms is the antiresonant interactions between them. $a_{\vec{k}}^\dagger$ is the creation operators of the cavity with in-plane wave vector $\vec{k}$ and energy $\hbar\omega_{cav,\vec{k}}$ and $b_{\vec{k}}^\dagger$, $d_{\vec{k}}^\dagger$ are respectively the creation operators of the electronic excitation mode of wave vector $\vec{k}$ and energy $\hbar\omega_{12}$, $\hbar\omega_{13}$. $\Omega_{12,\vec{k}}$, $\Omega_{13,\vec{k}}$ are the vacuum Rabi frequency of the cavity photon and the two electronic excitation which quantifies the strength of the light-matter dipole coupling and it can become a significant fraction of the intersubband transition. The explicit expression is

$$\Omega_{12(3),\vec{k}} = \left(\frac{2\pi e^2}{\varepsilon_\infty m_0 L_{cav}^{eff}} \sigma_{el} N_{QW} f_{12(3)} \sin^2\theta_1 \right)^{1/2} \tag{2}$$

where N_{QW} is the number of quantum wells present in the cavity, $\sigma_{el} = N_{el}/S$ is the electron density per unit area in the deep quantum wells, N_{el} is the number of the electron in deep well and S is the quantization area. L_{cav}^{eff} is the effective length of the cavity mode, ε_∞ is the cavity dielectric constant, and θ_1 is the intracavity probe photon propagation angle.

H are bilinear in the field operators and can be diagonalized through a Bogoliubov transformation. Three intersubband polariton annihilation operators can be introduced as following

$$\begin{aligned} c_{j,\vec{k}} &= w_{j,\vec{k}} a_{\vec{k}} + x_{j,\vec{k}} b_{\vec{k}} + y_{j,\vec{k}} d_{\vec{k}} + z_{j,\vec{k}} a_{-\vec{k}}^\dagger \\ &+ p_{j,\vec{k}} b_{-\vec{k}}^\dagger + q_{j,\vec{k}} d_{-\vec{k}}^\dagger \end{aligned} \tag{3}$$

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where $j \in \{1,2,3\}$. The Hamiltonian of the system can be written as

$$H = E_G + \sum_{j=1}^{3}\sum_{\vec{k}} \hbar\omega_{j,\vec{k}} c_{j,\vec{k}}^{\dagger} c_{j,\vec{k}} \tag{4}$$

where the constant term E_G is the vacuum energy and not considered here. The vectors

$$\vec{v}_{j,\vec{k}} = \left(w_{j,\vec{k}}, x_{j,\vec{k}}, y_{j,\vec{k}}, z_{j,\vec{k}}, p_{j,\vec{k}}, q_{j,\vec{k}}\right)^T \tag{5}$$

Inserting expression (5) into (1) and notes the Bose commutation rule

$$\left[c_{j,\vec{k}}, c_{j',\vec{k}'}^{\dagger}\right] = \delta_{j,j'}\delta_{\vec{k},\vec{k}'} \tag{6}$$

imposes the normalization condition

$$\begin{aligned} &w_{j,\vec{k}}^{*} w_{j',\vec{k}} + x_{j,\vec{k}}^{*} x_{j',\vec{k}} + y_{j,\vec{k}}^{*} y_{j',\vec{k}} - z_{j,\vec{k}}^{*} z_{j',\vec{k}} \\ &- p_{j,\vec{k}}^{*} p_{j',\vec{k}} - q_{j,\vec{k}}^{*} q_{j',\vec{k}} = \delta_{j,j'} \end{aligned} \tag{7}$$

We found five excitations should be taken into account which are related with the cavity mode and the two electronic transitions and treated as ensembles of quantum oscillators. In the double-sided cavity the cavity mode is coupled to two external electromagnetic field reservoirs through the front and back mirrors which are described by H^{ph} and $H^{ph'}$. where $\omega_{q,\vec{k}}^{ph}$ ($\omega_{q,\vec{k}}^{ph'}$) is the frequency of an extra-cavity photon with in-plane wave vector $\vec{k}$ and wave vector q in the orthogonal direction and $\alpha_{q,\vec{k}}^{\dagger}$ ($\alpha_{q,\vec{k}}'^{\dagger}$) is the corresponding creation operator, obeying the commutation rule

$$\left[\alpha_{q,\vec{k}}, \alpha_{q',\vec{k}'}^{\dagger}\right] = \delta(q-q')\delta_{\vec{k},\vec{k}'}$$

$$(\left[\alpha'_{q,\vec{k}}, \alpha_{q',\vec{k}'}'^{\dagger}\right] = \delta(q-q')\delta_{\vec{k},\vec{k}'}).$$

The coupling between the cavity and extracavity radiation fields is quantified by the tunneling matrix element $\kappa_{q,\vec{k}}^{ph}$ ($\kappa_{q,\vec{k}}^{ph'}$) through the cavity mirror. The damping and decoherence of the electronic transition is due to the interplay of different processes, such as the interaction with crystal phonons (optical and acoustical) and the scattering with impurities and with free carriers in levels other than the ones involved in the considered electronic transition. In the TIT media there is a shared continuum reservoir so the two electronic excitations are coupled by three baths which are H_2^{el}, H_3^{el} and H^{el}. Here, the bath operators $\beta_{2,q,\vec{k}}$ ($\beta_{3,q,\vec{k}}$) is only coupled to electronic transition from $|1\rangle$ to $|2\rangle$ ($|3\rangle$) and $\beta_{q,\vec{k}}$ is coupled to both. The operators satisfy the harmonic oscillator commutation rule and has frequency $\omega_{2,q,\vec{k}}^{el}$ ($\omega_{3,q,\vec{k}}^{el}$). $\kappa_{2,q,\vec{k}}^{el}$ are the matrix elements quantifying the coupling to the electronic polarization.

$$\begin{aligned}
H^{ph} &= \int dq \sum_{\vec{k}} \hbar\omega_{q,\vec{k}}^{ph}\left(\alpha_{q,\vec{k}}^{\dagger}\alpha_{q,\vec{k}} + \frac{1}{2}\right) \\
&\quad + i\hbar\int dq \sum_{\vec{k}}\left(\kappa_{q,\vec{k}}^{ph}\alpha_{q,\vec{k}}a_{\vec{k}}^{\dagger} - \kappa_{q,\vec{k}}^{ph*}\alpha_{q,\vec{k}}^{\dagger}a_{\vec{k}}\right) \\
H^{ph'} &= \int dq \sum_{\vec{k}} \hbar\omega_{q,\vec{k}}^{ph'}\left(\alpha_{q,\vec{k}}'^{\dagger}\alpha'_{q,\vec{k}} + \frac{1}{2}\right) \\
&\quad + i\hbar\int dq \sum_{\vec{k}}\left(\kappa_{q,\vec{k}}^{ph'}\alpha'_{q,\vec{k}}a_{\vec{k}}^{\dagger} - \kappa_{q,\vec{k}}^{ph*}\alpha_{q,\vec{k}}'^{\dagger}a_{\vec{k}}\right) \\
H_2^{el} &= \int dq \sum_{\vec{k}} \hbar\omega_{2,q,\vec{k}}^{el}\left(\beta_{2,q,\vec{k}}^{\dagger}\beta_{2,q,\vec{k}} + \frac{1}{2}\right) \\
&\quad + i\hbar\int dq \sum_{\vec{k}}\left(\kappa_{2,q,\vec{k}}^{el}\beta_{2,q,\vec{k}}b_{\vec{k}}^{\dagger} - \kappa_{2,q,\vec{k}}^{el*}\beta_{2,q,\vec{k}}^{\dagger}b_{\vec{k}}\right) \\
H_3^{el} &= \int dq \sum_{\vec{k}} \hbar\omega_{3,q,\vec{k}}^{el}\left(\beta_{3,q,\vec{k}}^{\dagger}\beta_{3,q,\vec{k}} + \frac{1}{2}\right) \\
&\quad + i\hbar\int dq \sum_{\vec{k}}\left(\kappa_{3,q,\vec{k}}^{el}\beta_{3,q,\vec{k}}d_{\vec{k}}^{\dagger} - \kappa_{3,q,\vec{k}}^{el*}\beta_{3,q,\vec{k}}^{\dagger}d_{\vec{k}}\right) \\
H^{el} &= \int dq \sum_{\vec{k}} \hbar\omega_{q,\vec{k}}^{el}\left(\beta_{q,\vec{k}}^{\dagger}\beta_{q,\vec{k}} + \frac{1}{2}\right) \\
&\quad + i\hbar\int dq \sum_{\vec{k}}\left(\kappa_{b,q,\vec{k}}^{el}\beta_{q,\vec{k}}b_{\vec{k}}^{\dagger} - \kappa_{b,q,\vec{k}}^{el*}\beta_{q,\vec{k}}^{\dagger}b_{\vec{k}}\right) \\
&\quad + i\hbar\int dq \sum_{\vec{k}}\left(\kappa_{d,q,\vec{k}}^{el}\beta_{q,\vec{k}}d_{\vec{k}}^{\dagger} - \kappa_{d,q,\vec{k}}^{el*}\beta_{q,\vec{k}}^{\dagger}d_{\vec{k}}\right)
\end{aligned} \tag{8}$$

3. Results

In the multiatoms-cavity system when the intracavity dark state is induced by a coupling laser in the cavity and multiple Λ-type atomic system, the cavity transmission spectrum exhibits three peaks shown in (a): two sidebands associated with the multiatom vacuum Rabi splitting and an ultranarrow central peak representing the cavity dark-state resonance of the two-photon Raman transition. In the quantum wells microcavity the ultranarrow polariton is a dark state which results from the coherent superposition of the cavity photons and the electronic transition. This is quantum interference phenomenon induced by multiple energy transfer pathways.

In order to show intracavity TIT characteristics we use the input-output theory to solve equation (1) and obtain the spectra of reflectivity (a), transmission (b) and absorption (c) spectra as functions of the incident photon energy E with (solid line) and without (dashed line) the antiresonant terms of the system and the external dissipation bath. The calculations have been performed for a symmetric double-sided cavity with double quantum well structure in Ref. [6]. The parameters are $\omega_{12} = 90$ meV, $\omega_{13} - \omega_{12} = 17.6$ meV, $\Gamma_2 = 5.6$ meV, $\Gamma_3 = 7.0$ meV. The parameters related with the cavity mode are chosen as $\Omega_{12,\vec{k}}$ meV and $\Gamma = 6$ meV where Γ is the loss of the cavity mode and Γ_2 and Γ_3 are decay rates of the two intersubband transitions. Other parameters are de-

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cided by the relations, $D_{\vec{k}} = 2\Omega^2_{12,\vec{k}} \big/ (\omega_{12} + \omega_{13})$

$$\omega_{cav,\vec{k}} + 2D_{\vec{k}} = (\omega_{12} + \omega_{13})\big/2 .$$

According to **Figures 2(a)** and **(b)**, a narrow dip or peak really demonstrate intracavity TIT in the reflectivity

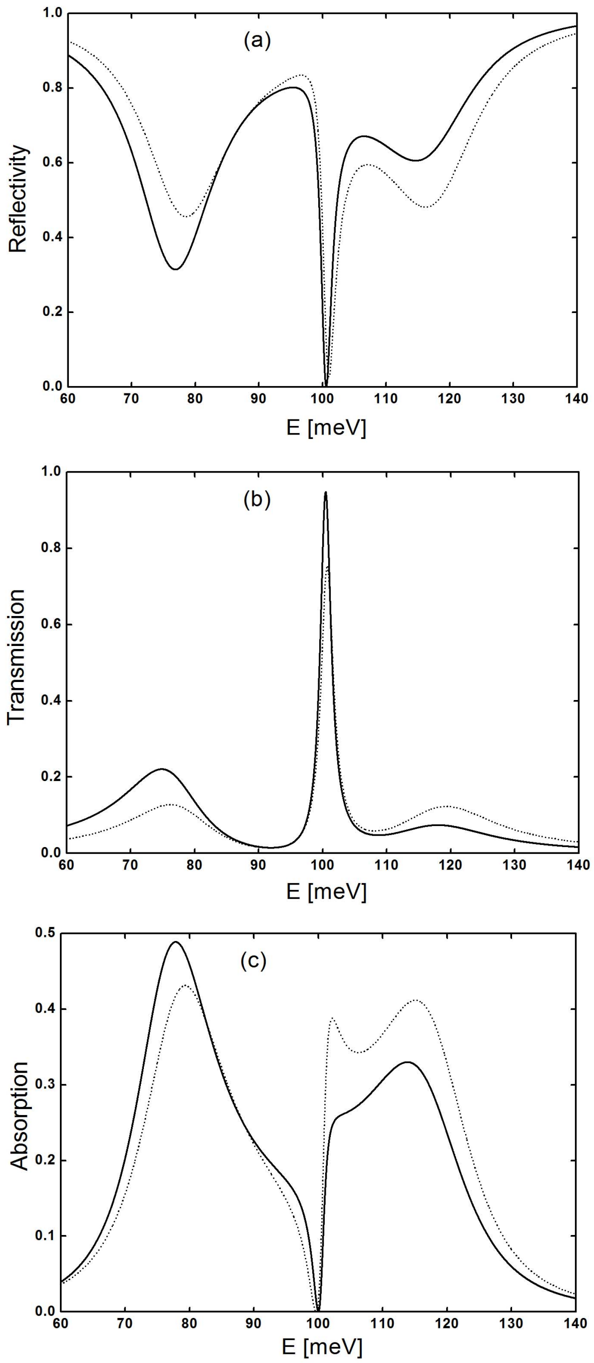

Figure 2. Transmission (a), absorption (b) and absorption (c) spectra as a function of the incident photon energy E with (solid line) and without (dashed line) the antiresonant terms of the system and the external dissipation bath. The calculations have been performed for a symmetric double-sided cavity with parameters in ref.[6].

and transmission spectra which shows that an asymmetric polariton can be produced at the transparent window at middle-infrared wavelength. The spectra are similar to those in three-levels atoms-cavity system which has two bandsides and a much narrow symmetric middle polariton [9]. The linewidth of the middle dip or peak is one-sixth of that in the bare cavity.

Secondly, the asymmetric degree between two bandsides got larger when the anti-resonant terms are considered than that without considering them. However the positions of the two Rabi splitting peaks are nearly the same. The anti-resonant terms results in the transmission enhancement of the left polariton and suppression of the right polariton. This is caused by asymmetric effect of quantum interference of two transition path due to anti-resonant interaction of the external dissipation bath. In the transmission spectra the transmission ratio of the two polaritions enhances about 72%.

Thirdly the absorption spectra shows that there is a zero absorption near TIT window caused by Fano interference of two transition path through two level $|2\rangle$ and $|3\rangle$ into the same continuum [10]. The anti-resonant terms leads to suppression of the resonant peak in an asymmetric absorption line profile at zero absorption position.

4. Conclusions

In conclusion, we prove intracavity TIT in an asymmetric double-quantum well microcavity can be realized in the ultrastrong-coupling regime. The quantum wells microcavity may be useful for the precision measurement and the control of the photons in the ultrastrong-coupling regime.

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