Spatially nonlocal effects on optical absorption properties in coupled quantum wells with an applied electric field*

Wang Chao-Yang(王晁阳)† and Wang Guang-Hui(王光辉)‡

Laboratory of Nanophotonic Functional Materials and Devices, South China Normal University, Guangzhou 510006, *China*

(Received 14 April 2014; revised manuscript received 3 July 2014; published online 10 October 2014)

Based on the microscopic nonlocal optical response theory, the intersubband optical absorption properties in AlGaAs/GaAs couple quantum wells (CQWs) are investigated for p-polarized states. The numerical results show that spatial nonlocality of optical responses can induce a radiation shift on optical absorption spectra due to nonlocal effects. The dependence of the radiation shift on the CQW structure and the applied electric field is clarified. It is also demonstrated that the maximal radiation shift and the least optical absorbance can be obtained by adopting an appropriate CQW structure and a suitable applied electric field. This work may provide some methods of designing the nanomaterials with controllable nonlocality and observing the spatial nonlocal effects in experiment.

Keywords: optical absorption, coupled quantum well, spatial nonlocality

PACS: 71.35.Cc, 68.65.Fg, 11.10.Lm **DOI:** 10.1088/1674-1056/23/12/127103

1. Introduction

In the past few years, linear and nonlinear optical properties of low-dimensional quantum systems, such as quantum wells (QWs), quantum dots (QDs), and other nanostructures, have attracted much interest from theoretical and applied aspects.[1–10] Most of the previous studies on the optical properties of the low-dimensional systems, however, are based on the local optical response theory, in which optical fields inside nanostructures are considered as invariant, and consequently optical susceptibility tensors $\overleftrightarrow{\chi}(\omega)$ are used to characterize optical properties of nanostructures. For example, in 2008, Chen *et al*. studied the second-order nonlinear optical susceptibility in asymmetric coupled quantum wells (CQWs), and showed a very large second-order optical susceptibility by optimizing the structural parameters.[11] In 2013, Choubani *et al*. investigated nonlinear optical rectification in vertically coupled InAs/GaAs QDs, and they also characterized the optical rectification effect by the second-order nonlinear optical susceptibility.[12]

Recently spatial nonlocality of the optical response in mesoscopic systems has drawn more and more attention,[13–18] since the pioneering theoretical work of Pekar and Ginzburg.[19,20] The so-called spatial nonlocality of optical response is that the polarization at a spatial point is induced by the applied optical fields not only at the same point, but also at other positions within the extent of the relevant wave function. Spatially nonlocal response theory has also developed towards nanostructures by Keller [21,22] and Cho,[23–25] giving rise to the further development of nonlocal theory and nonlocal optical properties in plasma, nanostructures, metamaterials, and so on. In 2009, Pollard *et al*.[26] studied optical nonlocalities in plasmonic nanorod metamaterials and demonstrated additional waves exist in the nanorod metamaterials due to spatial nonlocality of the optical response. McMahon *et al*.[27] investigated nonlocal optical responses of metal nanostructures with arbitrary shape, and indicated that nonlocal effects are particularly important in apex structures. However, spatially nonlocal effects in CQW nanostructures have not been clarified, especially in the case of an applied electric field. The physical motive of our paper is to demonstrate the influence of spatial nonlocality on optical absorption spectra, the mutual relationship between the spatial nonlocality and the coupling effects of electron wave functions in semiconductor CQWs, and the influence of an applied electric field on the optical performance.

This paper is organized as follows. In Section 2, a basic framework for the spatially nonlocal optical response of electrons to optical fields from intersubband transition in a CQW system is presented for p-polarized light. In Section 3, the numerical results and discussion are presented for AlGaAs/GaAs CQWs with an applied electric field. A brief summary is given in Section 4.

2. Nonlocal optical response in CQWs with an applied electric field

Let us consider AlGaAs/GaAs CQWs confined in the z direction, and the static electric field F is applied along the z direction, as shown in Fig. 1. Based on the effective mass

*Project supported by the National Natural Science Youth Foundation of China (Grant No. 60906042) and the National Natural Science Foundation of China (Grant Nos. 10974058 and 61178003).

†E-mail: jnykq4@yeah.net

‡Corresponding author. E-mail: wanggh@scnu.edu.cn

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approximation, the Schrödinger equation for electrons in conduction bands can be written as

$$\left[-\frac{\hbar^2}{2m^*}\nabla^2 + V(z) - eFz\right]\psi_{n,q}(\boldsymbol{r}) = E_{n,q}\psi_{n,q}(\boldsymbol{r}), \quad (1)$$

with the confinement potential $V(z)$

$$V(z) = \begin{cases} V_2, & z < -z_3, \\ 0, & -z_3 < z < -z_1, \\ V_1, & -z_1 < z < z_1, \\ 0, & z_1 < z < z_2, \\ V_2, & z > z_2, \end{cases} \quad (2)$$

where z represents the confinement direction of the CQWs; V_1 and V_2 denote the mid-barrier and outer barrier height in the case of no applied electric field, respectively; $\hbar$ is the Planck constant; e is the electron charge; F is the applied electric field; m^* is the effective mass of an electron in the conduction band; $\psi_{n,q}(\boldsymbol{r})$ and $E_{n,q}$ are the eigenfunctions and eigenenergies of the CQW system, respectively. Due to the system with the translational invariance in the xy plane and the confinement in the z direction, $\psi_{n,q}(\boldsymbol{r})$ and $E_{n,q}$ can be written as

$$\psi_{n,q}(\boldsymbol{r}) = \frac{1}{2\pi}\mathrm{e}^{\mathrm{i}\boldsymbol{q}_{||}\cdot\boldsymbol{r}_{||}}\varphi_n(z), \quad (3)$$

and

$$E_{n,q} = \varepsilon_n + \frac{\hbar^2}{2m^*}|\boldsymbol{q}_{||}|^2, \quad (4)$$

here, $\boldsymbol{q}_{||}$ and $\boldsymbol{r}_{||}$ are the electronic wave-vector and position vector in the xy plane. $\varphi_n(z)$ and ε_n, solutions of the one-dimensional Schrödinger equation $H_0\varphi_n(z) = \varepsilon_n\varphi_n(z)$, are called the envelope wave functions and the transverse energies of the n-th subband, respectively, where $H_0 = -(\hbar^2/2m^*)(\mathrm{d}^2/\mathrm{d}z^2) + V(z)$, being the z part of the total Hamiltonian H in Eq. (1).

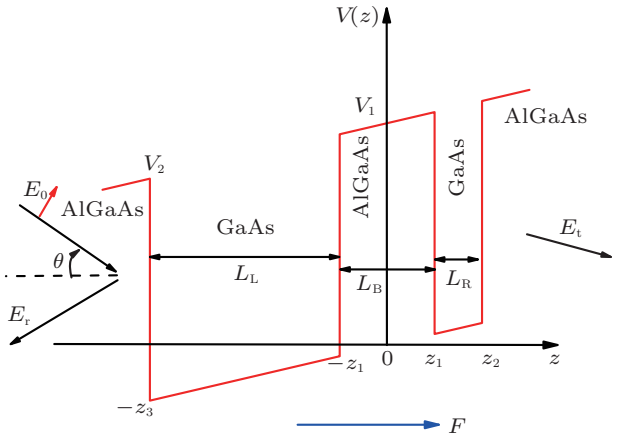


Fig. 1. (color online) The schematic diagrams of AlGaAs/GaAs CQWs with an applied electric field F oriented along the z direction, and the reflection field ($\boldsymbol{E}_\mathrm{r}$) and transmission field ($\boldsymbol{E}_\mathrm{t}$) of a p-polarized incident electric field ($\boldsymbol{E}_0$). L_R, L_L, and L_B denote the right-well, left-well, and mid-barrier widths, respectively.

For the finite-depth CQW, the transverse energy eigenvalue ε_n and the corresponding electronic envelope wave function $\varphi_n(z)$ in the CQW active layer can be expressed as

$$\varphi_n(z) = \begin{cases} a_n\exp(k_1 z), & z < -z_3; \\ b_{1n}\mathrm{Ai}(\xi_2 z) + b_{2n}\mathrm{Bi}(\xi_2 z), & -z_3 < z < -z_1; \\ c_{1n}\mathrm{Ai}(\xi_3 z) + c_{2n}\mathrm{Bi}(\xi_3 z), & -z_1 < z < z_1; \\ d_{1n}\mathrm{Ai}(\xi_2 z) + d_{2n}\mathrm{Bi}(\xi_2 z), & z_1 < z < z_2; \\ e_n\exp(-k_4 z), & z > z_2. \end{cases} \quad (5)$$

Where $k_1 = [2m^*(-\varepsilon_n + V_2)]^{1/2}/\hbar$, $\xi_2 = [(2m^*eF)/\hbar^2]^{1/3}[z + (eFz_3 - \varepsilon_n)/eF]$, $\xi_3 = [(2m^*e)/\hbar^2]^{1/3}[z + (eFz_3 - \varepsilon_n + V_1)/eF]$, $k_4 = \{2m^*[-\varepsilon_n + V_2 + eF(z_2 + z_3)]\}^{1/2}/\hbar$. These coefficients a_n, b_{1n}, b_{2n}, c_{1n}, c_{2n}, d_{1n}, d_{2n}, e_n, and the transverse energy eigenvalue ε_n can be obtained through the continuity of the envelope wave function at the boundaries.

In what follows, we assume a p-polarized and monochromatic plane-wave electromagnetic field is incident on the CQW with an angular frequency ω and an incident angle θ, as shown in Fig. 1. For time-harmonic electromagnetic fields, we can write $\boldsymbol{E}(\boldsymbol{r},t) = \mathrm{Re}\{\boldsymbol{E}(\boldsymbol{r},\omega)\exp(-\mathrm{i}\omega t)\}$, $\boldsymbol{B}(\boldsymbol{r},t) = \mathrm{Re}\{\boldsymbol{B}(\boldsymbol{r},\omega)\exp(-\mathrm{i}\omega t)\}$, and $\boldsymbol{P}(\boldsymbol{r},t) = \mathrm{Re}\{\boldsymbol{P}(\boldsymbol{r},\omega)\exp(-\mathrm{i}\omega t)\}$, where $\boldsymbol{E}(\boldsymbol{r},\omega)$, $\boldsymbol{B}(\boldsymbol{r},\omega)$, and $\boldsymbol{P}(\boldsymbol{r},\omega)$ are complex functions of position and frequency. Re denotes the real part. In the case of nonlocal linear response, the nonlocal relation between the induced resonant polarizability $\boldsymbol{P}(\boldsymbol{r},\omega)$ and complex electric field $\boldsymbol{E}(\boldsymbol{r},\omega)$ reads

$$\boldsymbol{P}(\boldsymbol{r},\omega) = \varepsilon_0\int \mathrm{d}\boldsymbol{r}'\overleftrightarrow{\chi}(\boldsymbol{r},\boldsymbol{r}';\omega)\cdot\boldsymbol{E}(\boldsymbol{r}',\omega), \quad (6)$$

where $\overleftrightarrow{\chi}$ denotes the nonlocal susceptibility tensors. Due to the system with the translational invariance in the x direction and the confinement in the z direction, the complex electric field $\boldsymbol{E}(\boldsymbol{r},\omega)$ and induced polarization $\boldsymbol{P}(\boldsymbol{r},\omega)$ can be assumed to have the forms $\boldsymbol{E}(\boldsymbol{r},\omega) = \widetilde{\boldsymbol{E}}(z;\omega)\exp(\mathrm{i}k_x x)$ and $\boldsymbol{P}(\boldsymbol{r},\omega) = \widetilde{\boldsymbol{P}}(z;\omega)\exp(\mathrm{i}k_x x)$, where k_x stands for the wave number in the x direction.

By substituting Eq. (6) into Maxwell equations, we can derive the integral–differential equation for the self-consistent complex electric field $\boldsymbol{E}(\boldsymbol{r},\omega)$ in the case of the nonlocal linear optical response,[21] viz.,

$$\overleftrightarrow{\Lambda}(\omega)\cdot\widetilde{\boldsymbol{E}}(z;\omega) = -\frac{\omega^2}{c^2}\int \mathrm{d}z'\overleftrightarrow{\chi}(z,z';\omega)\cdot\widetilde{\boldsymbol{E}}(z';\omega), \quad (7)$$

where the tensorial operator $\overleftrightarrow{\Lambda}(\omega) = \overleftrightarrow{I}[\omega^2/c^2\varepsilon^\mathrm{B}(\omega) - k_x^2 + \partial^2/\partial z^2] - (\mathrm{i}k_x\hat{e}_x + \hat{e}_z\partial/\partial z)(\mathrm{i}k_x\hat{e}_x + \hat{e}_z\partial/\partial z)$. Here c is the speed of light in a vacuum. $\overleftrightarrow{I}$ denotes the unit tensor. $\hat{e}_x$ and $\hat{e}_z$ denote unit vector in the x and z directions, respectively. $\varepsilon^\mathrm{B}(\omega)$ is the relative dielectric constant of the background medium. By the one-body density matrix method, its nonzero elements of the nonlocal linear susceptibility tensors for the

two-level CQW model can be obtained in the low-temperature ($T \to 0$) and long-wavelength ($k_x \to 0$) limits as follows:

$$\chi_{xx}(z,z';\omega) = -\frac{e^2}{2\pi\varepsilon_0\hbar^2\omega^2}\frac{(\varepsilon_{\rm F}-\varepsilon_1)^2\Psi(z)\Psi(z')}{\hbar\omega-\varepsilon_{21}+{\rm i}\hbar\Gamma}, \quad (8)$$

$$\chi_{zz}(z,z';\omega) = \frac{e^2}{4\pi\varepsilon_0 m^*\omega^2}\frac{(\varepsilon_1-\varepsilon_{\rm F})F(z)F(z')}{\hbar\omega-\varepsilon_{21}+{\rm i}\hbar\Gamma}, \quad (9)$$

where $\Psi(z) = \varphi_1(z)\varphi_2(z)$, and $F(z) = \varphi_1(z){\rm d}\varphi_2(z)/{\rm d}z - \varphi_2(z){\rm d}\varphi_1(z)/{\rm d}z$; $\varepsilon_{21} = \varepsilon_2 - \varepsilon_1$; Γ is the off-diagonal relaxation rate; $\varepsilon_{\rm F}$ is the Fermi energy of the CQW system.

By the Green's function method as mentioned in [21] and [23], one can solve the components of the complex electric field from Eq. (6) as follows:

$$\begin{aligned}\widetilde{E}_x(z;\omega) &= \widetilde{E}_{0x}(z;\omega) + \alpha N_x\int_{-\infty}^{\infty} G_{xx}(z,z';\omega)\Psi(z'){\rm d}z' \\ &\quad + \beta N_z\int_{-\infty}^{\infty} G_{xz}(z,z';\omega)F(z'){\rm d}z', \quad (10)\\ \widetilde{E}_z(z;\omega) &= \widetilde{E}_{0z}(z;\omega) + \alpha N_x\int_{-\infty}^{\infty} G_{zx}(z,z';\omega)\Psi(z'){\rm d}z' \\ &\quad + \beta N_z\int_{-\infty}^{\infty} G_{zz}(z,z';\omega)F(z'){\rm d}z', \quad (11)\end{aligned}$$

where $\widetilde{\boldsymbol{E}}_0(z;\omega) = \widetilde{\boldsymbol{E}}_0\exp({\rm i}k_\perp z)$ is the incident field, and $k_\perp = \sqrt{\varepsilon^{\rm B}\omega^2/c^2 - k_x^2}$ is the wave number in the z direction. $\alpha = \mu_0 e^2(\varepsilon_{\rm F}-\varepsilon_1)^2/(2\pi\hbar^2\Lambda)$, and $\beta = \mu_0 e^2(\varepsilon_{\rm F}-\varepsilon_1)/(4\pi m^*\Lambda)$, where $\Lambda = \hbar\omega - \varepsilon_{21} + i\hbar\Gamma$. In addition, we have defined two new variables: $N_x(\omega) \equiv \int_{-\infty}^{\infty}\Psi(z)\widetilde{E}_x(z;\omega){\rm d}z$, and $N_z(\omega) \equiv \int_{-\infty}^{\infty}F(z)\widetilde{E}_z(z;\omega){\rm d}z$. $G_{ij}(z,z';\omega)$ $(i,j = x,z)$ are the elements of the tensorial Green's function $\overleftrightarrow{G}(z,z';\omega)$ of the CQW system for p-polarized light

$$\begin{aligned}&\overleftrightarrow{G}(z,z';\omega)\\ &= \frac{k_x c^2\,{\rm e}^{{\rm i}k_\perp|z-z'|}}{2{\rm i}\varepsilon^{\rm B}\omega^2}\begin{pmatrix} k_\perp/k_x & \mathrm{sgn}(z'-z)\\ \mathrm{sgn}(z'-z) & k_x/k_\perp\end{pmatrix}\\ &\quad + \frac{\delta(z'-z)c^2}{\varepsilon^{\rm B}\omega^2}\hat{e}_z\hat{e}_z, \quad (12)\end{aligned}$$

where $\mathrm{sgn}(z)$ is the usual sign function.[21]

Multiplying both sides of Eqs. (10) and (11) by $\Psi(z)$ and $F(z)$, respectively, and integrating the two equations over z across the CQW, one can deduce immediately the two variables $N_x(\omega)$ and $N_z(\omega)$, namely, $N_x = [\widetilde{S}_x(1-\beta M_{zz}) + \beta\widetilde{S}_z M_{xz}]/\eta$, and $N_z = [\widetilde{S}_z(1-\alpha M_{xx}) + \alpha\widetilde{S}_x M_{zx}]/\eta$, where $\eta = (1-\alpha M_{xx})(1-\beta M_{zz}) - \alpha\beta M_{xz}M_{zx}$, $M_{xx} = \iint_{-\infty}^{\infty}\Psi(z)G_{xx}(z,z';\omega)\Psi(z'){\rm d}z{\rm d}z'$, $M_{xz} = -M_{zx} = \iint_{-\infty}^{\infty}\Psi(z)G_{xz}(z,z';\omega)F(z'){\rm d}z{\rm d}z'$, $M_{zz} = \iint_{-\infty}^{\infty}F(z)G_{zz}(z,z';\omega)F(z'){\rm d}z{\rm d}z'$, $\widetilde{S}_x = \int_{-\infty}^{\infty}\widetilde{E}_{0x}(z;\omega)\Psi(z){\rm d}z$, and $\widetilde{S}_z = \int_{-\infty}^{\infty}\widetilde{E}_{0z}(z;\omega)F(z){\rm d}z$.

To investigate the optical absorption spectra of the CQW, one must first determine the reflection and transmission coefficients. In other words, one should determine the field distribution outside the CQW first. By substituting Green's functions into Eqs. (10) and (11), and letting the observation point $z \to \pm\infty$, one can obtain the field distribution outside the CQW taking the asymptotic forms as follows:[16,21]

$$\begin{aligned}&\widetilde{\boldsymbol{E}}(z;\omega)\\ &= \boldsymbol{E}_0\,{\rm e}^{{\rm i}k_\perp z} + \left(1,0,\frac{k_x}{k_\perp}\right)\widetilde{E}_x^{\rm R}(\omega)\,{\rm e}^{-{\rm i}k_\perp z},\ z\to-\infty, \quad (13)\\ &\widetilde{\boldsymbol{E}}(z;\omega)\\ &= \boldsymbol{E}_0\,{\rm e}^{{\rm i}k_\perp z} + (1,0,-\frac{k_x}{k_\perp})\widetilde{E}_x^{\rm T}(\omega)\,{\rm e}^{{\rm i}k_\perp z},\ z\to\infty, \quad (14)\end{aligned}$$

with

$$\begin{aligned}\widetilde{E}_x^{\rm R}(\omega) &= \frac{c^2}{2{\rm i}\omega^2\varepsilon^{\rm B}}\int_{-\infty}^{\infty}[\alpha N_x k_\perp\Psi(z)\\ &\quad + \beta N_z k_x F(z)]\,{\rm e}^{{\rm i}k_\perp z}{\rm d}z, \quad (15)\\ \widetilde{E}_x^{\rm T}(\omega) &= \frac{c^2}{2{\rm i}\omega^2\varepsilon^{\rm B}}\int_{-\infty}^{\infty}[\alpha N_x k_\perp\Psi(z)\\ &\quad - \beta N_z k_x F(z)]\,{\rm e}^{-{\rm i}k_\perp z}{\rm d}z. \quad (16)\end{aligned}$$

Thus the reflectivity coefficient ($R_{\rm p}$) and transmittance coefficient ($T_{\rm p}$) of the CQW system are given as follows:

$$R_{\rm p} = \left|\frac{\widetilde{E}_x^{\rm R}(\omega)}{E_0\cos\theta}\right|^2,\quad T_{\rm p} = \left|1+\frac{\widetilde{E}_x^{\rm T}(\omega)}{E_0\cos\theta}\right|^2, \quad (17)$$

where θ is the incident angle. Thus the optical absorption coefficient (absorbance) is defined as

$$A_{\rm p} = 1 - R_{\rm p} - T_{\rm p}. \quad (18)$$

3. Results and discussion

In what follows, we will discuss the optical absorption spectra of AlGaAs/GaAs CQWs with an applied electric field in the case of taking spatial nonlocality of optical response into account. Some parameters used in the following calculation are adopted as:[16] $m^* = 0.067m_0$ (m_0 is the mass of a free electron); $\varepsilon_{\rm F} = \varepsilon_1 + \pi\hbar^2 N_{\rm f}/m^*$, where the surface donor concentration $N_{\rm f} = 10^{11}$ cm^{-2}; the relative dielectric constant of background medium $\varepsilon^{\rm B} = 13.1$; the relaxation energy $\hbar\Gamma = 4.7$ meV and the mid-barrier width $L_{\rm B} = 2$ nm.

In Fig. 2, optical absorption spectra are shown as a function of the normalized photon energy $\hbar\omega/\varepsilon_{21}$ for four different angles of incidence: 50°, 60°, 70°, and 80° with the CQW width ratio $L_{\rm R}/L_{\rm L} = 1/4$ ($L_{\rm L} = 12$ nm) and the barrier height ratio $V_1/V_2 = 1$ ($V_2 = 2.0\times10^{-19}$ J), and the applied electric field $F = 1.0\times10^7$ V/m. We can see from Fig. 2 that all of the positions of the resonance peaks occur at $\hbar\omega = 1.008\varepsilon_{21}$ for the asymmetric CQWs, which indicates that the resonant excitation energy $\hbar\omega$ does not equal the energy separation ε_{21}, but somewhat deviates from it. In other words, the resonant excitation energy is larger (or smaller) than the energy-level interval ε_{21}. This deviation is called radiation shift, which is attributed to the spatial nonlocality of optical response in the CQW system. The fact that the resonances appear at the same

position for any arbitrary incident angles indicates that the position of the resonance peak does not depend on the incident angle. The optical absorbance, however, is closely related to it. Generally speaking, the optical absorbance increases evidently by increasing the incident angle. The reason is that the z component of the incident field increases with the increase of the incident angle θ, which increases the intensity of the polarization of electrons in the z direction, then the quantum-size effect plays an important role in the z direction.

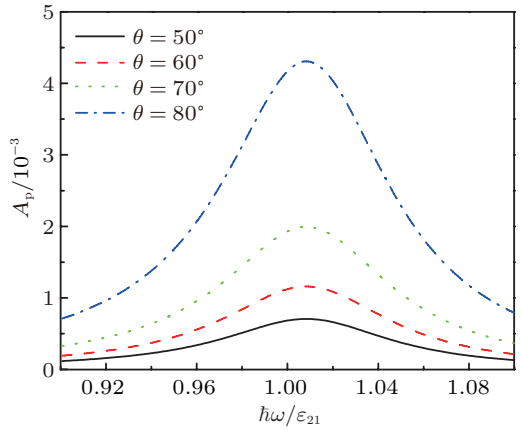


Fig. 2. (color online) Optical absorption spectra versus the normalized photon energy $\hbar\omega/\varepsilon_{21}$ for four different angles of incidence: 50°, 60°, 70°, and 80° with the CQW width ratio $L_R/L_L = 1/4$ ($L_L = 12$ nm), mid-barrier width $L_B = 2$ nm, and barrier height ratio $V_1/V_2 = 1$ ($V_2 = 2.0 \times 10^{-19}$ J).

In order to understand how optical absorption spectra depend on the well-width ratio of the CQWs in the presence of an applied electric field, we show the normalized position of the resonance peak ($\hbar\omega/\varepsilon_{21}$) in Fig. 3 and the corresponding optical absorbance at resonance in Fig. 4 as a function of normalized left-well width L_L/L_R (blue dotted line) with $L_R = 4$ nm, and as a function of normalized right-well width L_R/L_L (red dashed line) with $L_L = 4$ nm in the presence of the applied electric field $F = 1.0 \times 10^7$ V/m, compared with the case of without the applied electric field (black solid line). Without loss of generality, we have chosen the incident angle $\theta = 70°$ and the CQW barrier height ratio $V_1/V_2 = 1$ ($V_2 = 2.0 \times 10^{-19}$ J). It can be seen easily from Fig. 3 that a maximum radiation shift occurs at the well width ratio $L_R/L_L = 1$ when $F = 0$. This indicates that without applied electric fields, the coupling effects between the left- and right-wells of CQWs are the strongest in symmetric CQWs. When there is an applied electric field, however, the position of the maximum radiation shift has a deviation from the point of symmetry $L_R/L_L = 1$. This is because the CQW becomes asymmetric in the presence of an applied electric field; the position of the strongest coupling effect is changed. Figure 3 also tells us when $L_L/L_R > 5$ or $L_R/L_L > 5$, the position of the resonance peak changes slowly, and gradually tends to be the same, which is different from that in the absence of an applied electric field. This is because when the width of one well is much larger than the other, the CQW can be regarded as a single QW under the influence of the applied electric field. We can see the change rule of the position of the resonance peak is similar to the phenomena produced in the single QW with an applied electric field.[17]

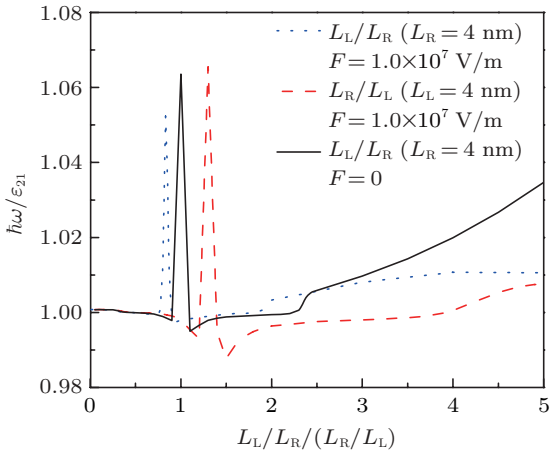


Fig. 3. (color online) The position of the resonance peak versus the structure parameter L_L/L_R ($L_R = 4$ nm, blue dotted line) or L_R/L_L ($L_L = 4$ nm, red dashed line) with $F = 10^7$ V/m, and versus L_L/L_R ($L_R = 4$ nm, black solid line) without F. In addition, $V_1 = V_2 = 2.0 \times 10^{-19}$ J and $\theta = 70°$.

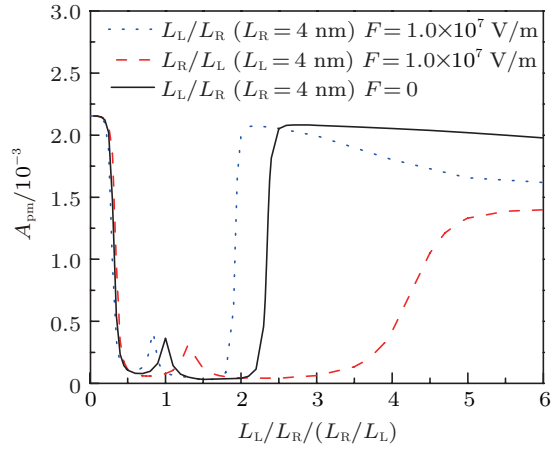


Fig. 4. (color online) The maximum optical absorbance A_{pm} at resonance versus the structure parameter L_L/L_R ($L_R = 4$ nm, blue dotted line) or L_R/L_L ($L_L = 4$ nm, red dashed line) with $F = 10^7$ V/m, and versus L_L/L_R ($L_R = 4$ nm, black solid line) without F. In addition, $V_1 = V_2 = 2.0 \times 10^{-19}$ J and $\theta = 70°$.

From Fig. 4, we can see that the resonant optical absorbance can be modulated by the structure parameters (well width ratio) of the CQW and the applied electric field. It is well known that when optical absorbance is very small at a certain range of well width, the windows can be considered as transparent. Compared with the case of no applied electric field (solid line), the transparent windows can be modulated by the applied electric field, as shown in Fig. 4. For a CQW of a fixed width of the left well, by exerting an applied electric

field, the transparent windows become wider than that without an applied electric field. However, when the width of the right well is fixed, by exerting an applied electric field, the transparent windows become narrower than that without an applied electric field. In addition, we can see that when $L_R/L_L = 0$ or $L_L/L_R = 0$, the CQW becomes a single QW, and optical absorbance is maximum. These properties indicate that the optical absorbance of a low-dimensional QW system can decrease by introducing the CQW nanostructures, and can be adjusted by an applied electric field.

To see how the applied electric field F influences optical absorption spectra, we plot the radiation shift ($\Delta\hbar\omega = \hbar\omega/\varepsilon_{21} - 1$) at resonance in Fig. 5 and the corresponding optical absorbance in Fig. 6 versus the applied electric field F for three different barrier height ratios: $V_1/V_2 = 0.3$ (solid line), $V_1/V_2 = 0.6$ (dashed line), $V_1/V_2 = 1$ (dotted line) with the outer barrier height $V_2 = 2.0 \times 10^{-19}$ J, the well width ratios $L_L/L_R = 1/4$ ($L_R = 4$ nm) and the incident angle $\theta = 70°$. From Fig. 5, we can see that the radiation shift creates a peak by increasing the applied electric field, and the higher the mid-barrier is, the greater the peak position corresponding to the applied electric field F will be. This is because the effective width of the left and right wells of CQWs is changed by the applied electric field. Generally speaking, when the right well is wider than the left well, in other words, the distance from the right well to the zero point of potential energy which we selected is also further than the distance from the left well, the right well shallows faster than the left well by enhancing the applied electric field. When F reaches a certain degree (the higher the barrier potential V_1 is, the larger the needed F will be), the left and right wells can trend towards approximately symmetric. For this reason, the coupling effect between the left and right wells is at its strongest, which induces the nonlocal effects to be at its strongest. Consequently, the radiation shift $\Delta\hbar\omega$ will be at its maximum value. In other positions away from the peak, however, we can see that the higher the barrier potential V_1, the smaller the radiation shift $\Delta\hbar\omega$ will be. This is because when the higher barrier potential V_1 decreases the coupling effect decreases between the left and right wells of the CQWs.

In Fig. 6, one can see the maximum optical absorbance A_{pm} at resonance decreases with the increase of the applied electric field at first, then A_{pm} has a peak at some F values corresponding to the peak position of the radiation shift $\Delta\hbar\omega$. From Fig. 6, we can also come to a conclusion that when $F > 3.75 \times 10^7$ V/m approximatively, the higher the mid-barrier is, the bigger the absorption will be. By comparing Fig. 5 with Fig. 6, we note that the optical properties can be modulated by the applied electric field F. Therefore, to obtain a large radiation shift and a relatively weaker optical absorbance, a suitable applied electric field should be adopted.

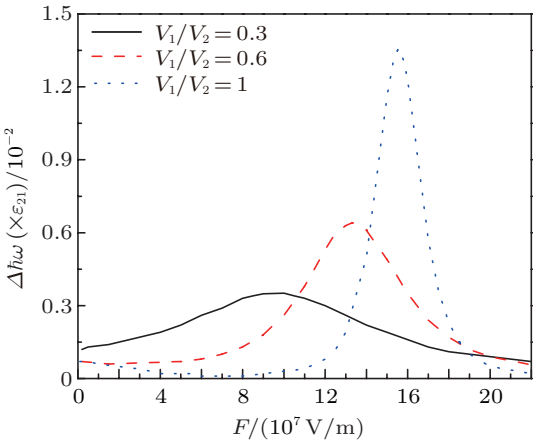


Fig. 5. (color online) The radiation shift ($\Delta\hbar\omega$) versus the applied electric field F for three different barrier-height ratios: $V_1/V_2 = 0.3$ (solid line), $V_1/V_2 = 0.6$ (dashed line), $V_1/V_2 = 1$ (dotted line) with $V_2 = 2.0 \times 10^{-19}$ J, $L_L/L_R = 1/4$ ($L_R = 4$ nm), and $\theta = 70°$.

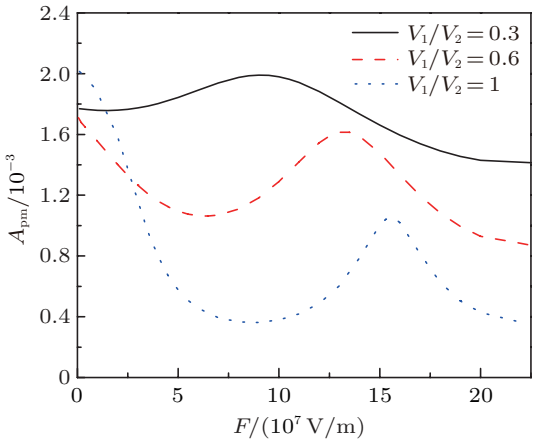


Fig. 6. (color online) The maximum optical absorbance A_{pm} at resonance versus the applied electric field F for three different barrier-height ratios: $V_1/V_2 = 0.3$ (solid line), $V_1/V_2 = 0.6$ (dashed line), $V_1/V_2 = 1$ (dotted line) with $V_2 = 2.0 \times 10^{-19}$ J, and $\theta = 70°$.

Figure 7 shows the radiation shift ($\Delta\hbar\omega$) versus the mid-barrier potential V_1 for three different applied electric fields: $F = 9 \times 10^7$ V/m (solid line), $F = 13 \times 10^7$ V/m (dashed line), $F = 15.5 \times 10^7$ V/m (dotted line), where we take $\theta = 70°$, $V_2 = 2.0 \times 10^{-19}$ J, and CQW width ratio $L_L/L_R = 1/4$ ($L_R = 4$ nm). In Fig. 7, we can see that the radiation shift ($\Delta\hbar\omega$) firstly increases to a maximum as the mid-barrier height increases, then decreases gradually. This can be understood by the following explanations. When $V_1 = 0$, the CQW becomes a single QW, consequently the radiation shift ($\Delta\hbar\omega$) is small. As the mid-barrier height V_1 increases, the single QW becomes a strongly coupled CQW, therefore the radiation shift ($\Delta\hbar\omega$) attains a maximum value. Then by further increasing V_1, the coupling effects decrease gradually, and consequently the nonlocal effects become weaker which induces a decrease in the radiation shift ($\Delta\hbar\omega$). This property indicates that nonlocal effects in CQWs are stronger than those in a single QW. In addition, we can see that the greater F is, the larger the maximum value of $\Delta\hbar\omega$ will be and the corresponding V_1 is required to be higher. This is because the emergence of the strongest couple

effects need a higher mid-barrier in the case of a larger applied electric field.

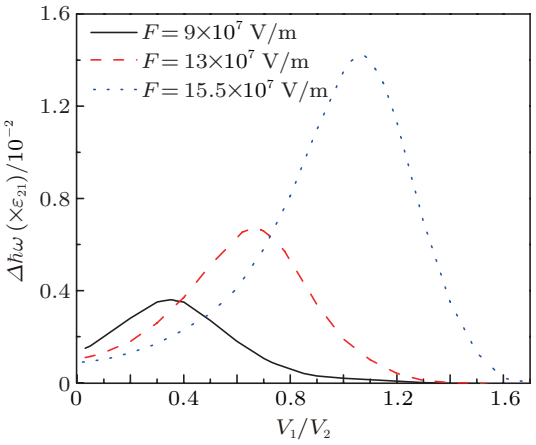


Fig. 7. (color online) The radiation shift ($\Delta\hbar\omega$) versus the barrier potential V_1 for three different values of the applied electric field: $F = 9 \times 10^7$ V/m (solid line), $F = 13 \times 10^7$ V/m (dashed line), $F = 15.5 \times 10^7$ V/cm (dotted line) with $\theta = 70°$, $V_2 = 2.0 \times 10^{-19}$ J, and $L_L/L_R = 1/4$ ($L_R = 4$ nm).

4. Summary

In this paper, the nonlocal effects on optical absorption spectra from the intersubband transition in AlGaAs/GaAs CQWs with an applied electric field are investigated for a p-polarized state based on the spatial nonlocal response theory. The numerical results show that the spatial nonlocality of optical responses can lead optical absorption spectra to have a radiation shift, which depends closely on the CQW structure parameters and the applied electric field. In addition, we also demonstrate that the maximal radiation shift and the least optical absorbance can be obtained by adopting an optimized CQW structure and a suitable applied electric field. These properties have potential applications to enhance or suppress the spatial dispersion and decrease the absorption loss in an optical device.

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