Terahertz wave generation in coupled quantum dots*

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(Received 8 August 2011; revised manuscript received 23 September 2011)

Based on coupled quantum dots, we present an interesting optical effect in a four-level loop coupled system. Both the two upper levels and the two lower levels are designed to be almost degenerate, which induces a considerable dipole moment. The terahertz wave is obtained from the low-frequency component of the photon emission spectrum. The frequency of the terahertz wave can be controlled by tuning the energy levels via designing the nanostructure appropriately or tuning the driving laser field. A terahertz wave with adjustable frequency and considerable intensity (100 times higher than that of the Rayleigh line) can be obtained. It provides an effective scheme for a terahertz source.

Keywords: coupled quantum dot, terahertz wave

PACS: 78.66.Fd, 78.67.Hc, 73.21.–b **DOI:** 10.1088/1674-1056/21/3/037804

1. Introduction

A great deal of attention has been paid to the generation of terahertz (THz) radiation (typically 0.1–10 THz), which lies in the frequency gap between infrared and microwave radiation, due to its important properties and significant applications in information and communication technologies, biological and medical sciences, homeland security, and global environmental monitoring, etc.[1] However, the generation of THz waves is a challengeable issue due to the lack of natural objects with a suitable energy spectrum. Benefitting from the technological innovations in photonics and nanotechnology, the situation has changed greatly during the last decade.

The THz wave can be obtained by both electronic[2] and optical methods.[3–7] The development of quantum cascade laser[8–13] based on semiconductor superlattices is a breakthrough for THz wave generation. Many researchers have also studied other sources.[14–19] Recently, an interesting approach based on semiconductor nanostructures driven by acoustic waves was suggested,[20] and a photonic–crystal THz laser pumped electrically was developed.[21] Moreover, THz wave generation by using the up-conversion method through high-order harmonic generation (HHG) in a semiconductor quantum dot (QD) was also suggested in our previous work.[22] Despite many studies, there is still an urgent requirement to improve the THz sources, especially the requirement for powerful THz sources. There are several promising techniques used for the realization of high-intensity THz sources, such as the accelerator-based laser, ultrashort electron-bunch transition, and the synchrotron radiation mechanism.[23] Other types of intense THz source can be produced by the laser-induced wakefields in plasma via linear mode conversion,[24] or by femtosecond electron bunches at a plasma–vacuum boundary via transition radiation.[25]

In strong laser fields, the emission spectra contain a Rabi frequency[26] that is much smaller than the frequency of the driven laser (located in the low-frequency region). It is an effective method to obtain THz waves from Rabi frequency components by using the laser field at a higher fundamental frequency. For quantum systems with inversion symmetry, the minimal radiation frequency is close to the incident laser frequency. One should break the inversion symmetry of the atomic and molecular systems to obtain low-frequency radiation corresponding to slow oscillations which can be realized by the degenerated energy levels combined with the initial coherent superposition states of a certain parity or applying a weak static electric field.[27] The terahertz emission from the Rabi frequency components due to the parametric oscillator behaviour of a two-level system with broken inversion symmetry exposed to a strong electromagnetic field is theoretically demonstrated to be experimen-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 10874020 and 11074025) and the National Basic Research Program of China (Grant No. 2011CB922204).

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tally observable.[5] Many theoretical studies have been carried out for low-frequency components of photon emission spectra,[28−32] most of which require coherent superposition states.

An interesting issue of THz wave generation is the generation of high-power radiation from the low frequency component of a photon emission spectrum in coupled QD systems, which are more flexible than atomic and molecular systems in tuning structure parameters, such as the size of the QDs, inter-dot distance or the relative position of the dots, and the height and width of the tunneling barriers. In this paper, we propose a scheme for the generation of powerful THz radiation in a four-level system based on double coupled InAs quantum dot system where sub-interband and band-to-band transitions are considered. Compared with the three-level system in an atom (or a molecule), the four-level system is superior in terms of adjustability. A laser at 50 THz is used as the driven field, which implies that the single electron approximation is appropriate, considering the life time of an exciton is about 1 ns. By designing the structure of degenerate levels to induce considerable dipole moment,[27] a considerable strength of THz radiation can be obtained, without considering the initial coherent superposition state or the external electric field. The frequency of the THz radiation can be controlled either by tuning the energy levels of QDs or the magnitude of the external field. Furthermore, the intensity of THz waves is raised by enhancing the dipole coupling between two degenerate levels.

2. Calculation

We consider a four-level ($|i\rangle, i = 1, 2, 3, 4$) loop coupled quantum system. The two upper levels $|1\rangle$ and $|2\rangle$, as well as the two lower levels $|3\rangle$ and $|4\rangle$, are both dipole coupled. Levels $|2\rangle$ and $|3\rangle$, as well as levels $|1\rangle$ and $|4\rangle$ are both dipole coupled from band to band with a resonance band gap $(\varepsilon_2 - \varepsilon_3) = 1$. Here, ε_i is the energy of level $|i\rangle$. A linearly polarized driven field at a frequency of ω_0 ($\omega_0/2\pi = 50$ THz) is used. By treating the driven field semiclassically and in the dipole approximation, the Schrödinger equation in the energetic representation, i.e., the set of equations for the probability amplitudes a_i is as follows ($\hbar = 1$):

$$\mathrm{i}\frac{\mathrm{d}a_i}{\mathrm{d}t} = \varepsilon_i a_i + \sum_{j=1}^{4} G_{ij}(t)a_j, \tag{1}$$

where $G_{ij}(t) = \boldsymbol{F}(t)\cdot\boldsymbol{\mu}_{ij}$ is the Rabi frequency caused by a periodic laser field $\boldsymbol{F}(t) = E\sin(\omega_0 t)\boldsymbol{e}$. Herein, E is the magnitude of the laser field, $\boldsymbol{e}$ is the unit polarization vector, $\boldsymbol{\mu}_{ij} = \langle i|e\boldsymbol{r}|j\rangle$ is the dipole between state $|i\rangle$ and state $|j\rangle$, and e is the charge of an electron.

With the help of Fourier transformation we can obtain the intensity of the emission spectrum $S(\nu) = |\int \mathrm{d}t\exp(-\mathrm{i}\nu t)\boldsymbol{D}(t)|^2$, where $\boldsymbol{D}(t) = \langle\psi(t)|\boldsymbol{D}|\psi(t)\rangle$ is the time-dependent expectation value of the dipole operator and $\psi(t) = \sum_{i=1}^{4} a_i(t)|i\rangle$ is the time-developed initial state. We set the photon energy of the driving field $\hbar\omega_0$ as the unit of energy. The electron is initially set at the lowest level. Low-frequency radiation is generated and controlled by setting system parameters appropriately, such as the energy spacing, the magnitude of the external field, and the dipole coupling, as will be displayed in the following section. If not mentioned specially, ε_i satisfies $\varepsilon_1 = \varepsilon_2$ and $\varepsilon_3 = \varepsilon_4$, with the resonance energy spacing $\varepsilon_2 - \varepsilon_3 = 1$. The magnitude of the external field $E = 0.3$ and the dipoles satisfy $\mu_{12} = \mu_{23} = \mu_{34} = \mu_{14} = 0.6$ e·nm, which are verified both experimentally and theoretically to be appropriate values in QDs.[33,34]

3. Results and discussion

With the help of numerical calculation, we propose a method to generate and optimize the THz radiation. As will be depicted in the last section, a four-level quantum system is considered. In what follows, we will realize the related optical processes in InAs double perpendicular coupled QDs based on both subinterband and band-to-band transitions.

As shown in Fig. 1, one InAs QD contains levels $|1\rangle$ and $|2\rangle$, which are from the conduction band, and the other InAs QD contains levels $|4\rangle$ and $|3\rangle$, which are from the valence band. Both the two upper levels $|1\rangle$ and $|2\rangle$, and the two lower levels $|3\rangle$ and $|4\rangle$ are dipole coupled (dashed lines in Fig. 1(b)). Meanwhile, levels $|2\rangle$ and $|3\rangle$ ($|1\rangle$ and $|4\rangle$) are dipole coupled from band to band with resonance band gap. The higher states within conduction or valence bands do not affect our conclusion. Firstly, for band-to-band transitions in our system (initial vacuum state), the low-energy excited states are dark states. That is to say, the transitions from the ground states in valence band to the excited states in conduction band are forbidden. Secondly, the probability of interband transitions is much smaller than the recombination probability of the excitons. Thus, it is reasonable to ignore the higher states within conduction and valence bands. Combining the two upper degenerate levels and the two lower

degenerate levels, the four-level system is appropriate to describe the double coupled QD system.

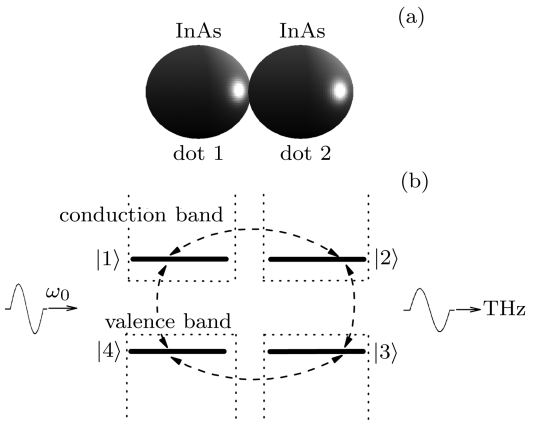


Fig. 1. (a) Simulated model of InAs double coupled QDs. (b) Schematic representation of the four-level system and the related optical processes.

Under the linearly polarized driven field, the energy spacing in our theoretical model is 0.42 eV, which matches the interband energy gap of InAs QD. One can tune the size of InAs QDs, the inter-dot distance, the height and width of the tunneling barriers to control the subinterband energy to realize the designated THz frequency, as will be presented later. The great tunableness of coupled QDs makes the four-level system a prior model as compared with the two- and three-level systems realized in atom/molecular.

As described above, THz radiation is obtained from the low-frequency components of photon emission spectra, which can be controlled by designing the nanostructure or tuning the external field. Let us first consider the generation of THz radiation. Meanwhile, we are interested in showing how the dipole coupling affects the intensity of THz radiations in the double-dot system. Take both the two upper and the two lower degenerate levels as examples, for the typical condition, i.e., the dipole coupling between the two upper levels μ_{12} is almost equal to that between other two levels, THz lines are generated and their intensity is lower than that of the Rayleigh line (the line at 50 THz in the spectrum as shown in Fig. 2(a)), which is usually the most intense line in the emission spectra. An optimized approach to obtain powerful THz waves experimentally by increasing the coupling between the two upper states is presented in Fig. 2(b). One can see an interesting phenomenon that the intensity of the low-frequency component is enhanced to a considerable value which is even 1000 times higher than that of the Rayleigh line. In this case, the enhanced intensity of the low-frequency emission is due to the degeneration of the two upper levels, which induces a large dipole moment.

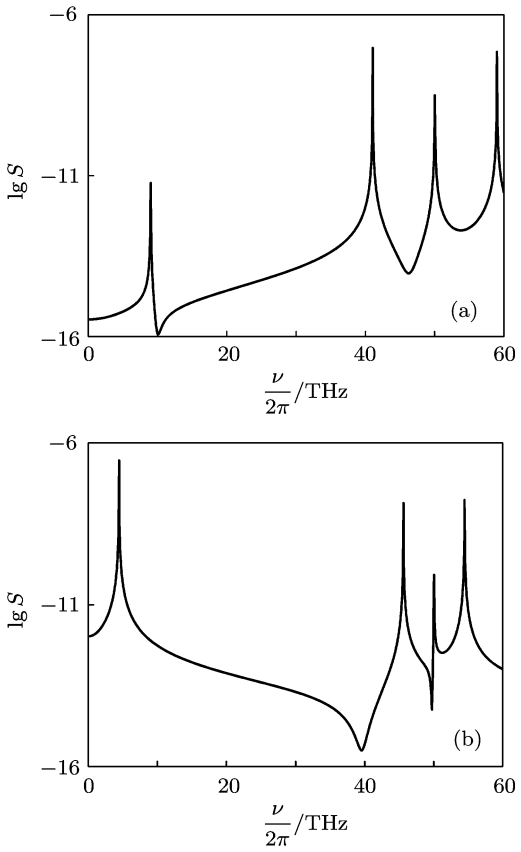


Fig. 2. Low-frequency parts of radiation spectra for the four-level quantum system of different dipole couplings: (a) spectrum of dipole coupling $\mu_{12} = 0.2$ e·nm; (b) optimized spectrum, the THz radiation is greatly enhanced due to larger dipole coupling $\mu_{12} = 8$ e·nm.

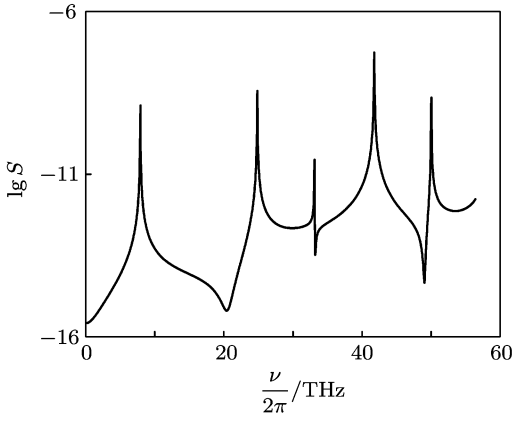


Fig. 3. Low-frequency part of radiation spectrum for dipole couplings $\mu_{12} = 0.6$ e·nm and $\mu_{23} = 8$ e·nm.

To make the physical picture clearer, we show the emission spectrum for a larger value of μ_{23}, the coupling between state $|2\rangle$ and state $|3\rangle$, which are non-degenerate. One can clearly see in Fig. 3 that the

intensity of the low-frequency component of the spectrum is not enhanced, yet it is weaker than that of the Rayleigh line.

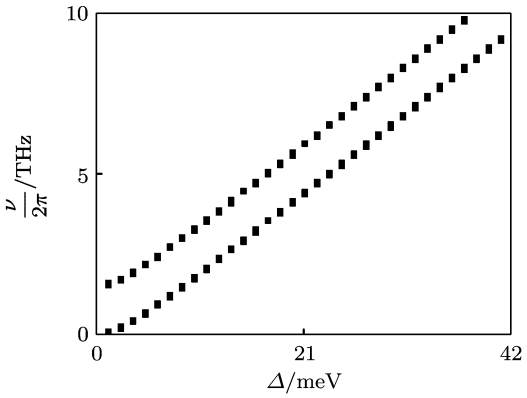


Fig. 4. Generated low-frequency radiation lines fully fill the THz gap as the energy spacing Δ is enlarged, where $\Delta = \varepsilon_1 - \varepsilon_2 = \varepsilon_3 - \varepsilon_4$, and $\varepsilon_2 - \varepsilon_3 = 1$.

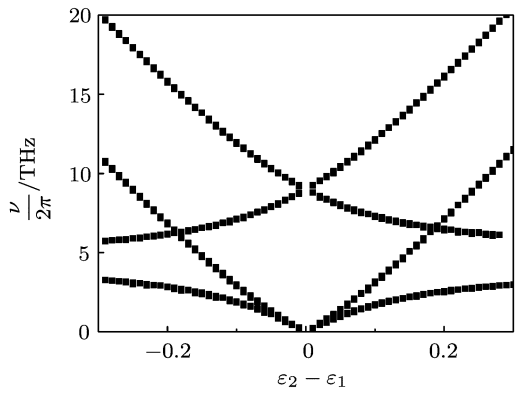


Fig. 5. Generated low-frequency radiation lines fully fill the THz gap as the energy spacing $\varepsilon_2 - \varepsilon_1$ changes, where $\varepsilon_3 = \varepsilon_4$, and $\varepsilon_1 - \varepsilon_3 = 1$.

Next we provide two schemes to obtain THz waves at a designated frequency, one by tuning the energy spacings (as shown in Figs. 4 and 5), the other by tuning the magnitude of the external field E (as shown in Fig. 6). In the first scheme, level energies ε_2 and ε_3 are fixed simultaneously, level energy ε_1 is tuned upwards, and level energy ε_4 is tuned in the opposite direction in step. In other words, we realize the process of designating the THz frequency by increasing the energy spacings between two upper levels $\varepsilon_1 - \varepsilon_2$ and two lower levels $\varepsilon_3 - \varepsilon_4$ simultaneously. It can be seen from Fig. 4 that radiation of 5 THz can be obtained by tuning the spacings to be 17.4 meV. More abundant radiation spectra can be obtained by simply moving one (e.g., ε_2) of the four levels, as shown in Fig. 5. An interesting zero point appears in Fig. 5, where there is no low-frequency signal due to the particular spatial–temporal symmetry[35] of the system. This point can be applied to make switches using the THz waves. In the latter scheme, one can see from Fig. 6 that the position of the THz radiation line shifts from the low-frequency end of the THz gap to the high-frequency end (from 0.1 to 10 THz) as the magnitude of external field increases. In other words, any designated frequency of terahertz waves can be obtained in this situation. For example, radiation at 9 THz can be obtained by tuning the magnitude of the external field $E = 0.3$ (in units of $1/\mu_{ij}$).

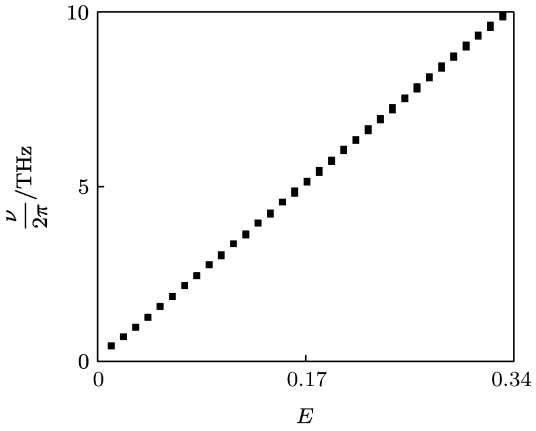


Fig. 6. Generated low-frequency radiation line fully fills the THz gap as the magnitude of the external field increases.

4. Conclusion

Based on both the interband and band-to-band transitions in double coupled QDs, a considerable strength of THz radiation is obtained from the low-frequency component of the photon emission spectra. Two schemes are proposed to gain an arbitrary frequency from 0.1 THz to 10 THz, one by tuning the external field, the other by tuning the energy levels. For a powerful THz source, optimized values of dipole couplings are found based on the degeneration of the levels, which induces a considerable dipole moment. Our model proposed here provides an effective scheme to obtain a considerable strength of THz waves experimentally.

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