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Terahertz resonance fluorescence and squeezing in quantum dots: Effects of external electric field and dimension

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ABSTRACT

The resonance fluorescence and phase-dependent spectrum in a typical quantum dot under the influence of an external electric field with attention to intersubband transitions driven by a laser field is studied. Finding energy eigenvalues and functions of the system, optical transition rates and Rabi frequency are calculated and effects of an external electric field and quantum dimension on the resonance fluorescence, squeezing and population of energy levels are investigated. Results show the fluorescence characteristics in Terahertz region of electromagnetic radiation strongly depend on external field and quantum dot dimensions. It is possible to control the resonance fluorescence and related phenomena via external factors and precise engineering of the system.

1. Introduction

In 1969 Mollow predicted that when a two level quantum system is strongly pumped near its resonance, it reemits light not only at the resonance frequency but also at two satellite frequencies. The prediction of this phenomenon is a major result of quantum optics theory. Resonance fluorescence (RF), i.e., the scattering of light from free atoms that are irradiated with a near-resonant field, is a central topic in quantum optics that has been carefully explored in theory and experiment [1–4].

Semiconductor quantum dots (QDs) are analogous to real atoms and their optical properties closely resemble the ones found in atomic physics [5–8]. The possibility for effective control of their physical properties by using external gates and fields [9,10], occurrence of the inter subband transitions with large transition dipole moments and emission or absorption in THz region have made them excellent successor instead of atomic systems in optical devices [11–15]. Many quantum optical effects such as coherent manipulation of exciton wave functions [16], optical pumping [17–22], coherent population trapping [23–26], single photon generation [27,28], and their potential applications in quantum information theory [29,30] are the subject of recent theoretical and experimental works [31,32]. In addition resonance florescence and quadrature squeezing of photons from QDs have also provided a versatile tool in modern quantum optical phenomena [33,34].

Although in the most works devoted to study the RF in semiconductors and nanostructures interband transitions are considered generally [35–38], in the current work we have studied RF, squeezing and population of states for intersubband transition in a typical GaAs QD under the influence of an external electric field. In contrast of previous works optical emission rates and Rabi frequency are calculated numerically using energy eigenvalues and functions of the system. Results show the possibility to control the RF, squeezing and population of states by external field and size of the QD in THz region of electromagnetic radiation.

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2. Theoretical model

Considering a 2-level QD, the Hamiltonian that governs the dynamics of the QD can be expressed as

$$H = H_0 + H_{Int} \tag{1}$$

The free Hamiltonian H_0 of the two-level system reads as

$$H_0 = \sum_{j=1}^{2} E_j \sigma_{jj} \tag{2}$$

where $E_j = \hbar\omega_j$ is the energy of the jth QD level and $\sigma_{ij} = |i\rangle\langle j|$ $(i, j = 1, 2)$ are the Pauli operators of the excitation. The interaction Hamiltonian, H_{Int}, which is written as

$$H_{Int} = -\hbar\Omega\sigma_{12}e^{-i\omega_L t} - \hbar\Omega\sigma_{21}e^{-i\omega_L t} + H.c. \tag{3}$$

accounts for the interaction of the QD with a monochromatic optical field of angular frequency ω_L which drives transition $|1\rangle \leftrightarrow |2\rangle$ with Rabi frequency Ω. The Hamiltonian in an appropriate rotating frame reads as

$$H = \frac{1}{2}\hbar\delta(\sigma_{22} - \sigma_{11}) - \hbar\Omega\sigma_{21} - \hbar\Omega^*\sigma_{12} \tag{4}$$

where $\delta = \omega_{21} - \omega_L$ denotes the optical detuning. We can write the density matrix equations of motion of the system as

$$\begin{aligned}
\frac{\partial\rho_{12}}{\partial t} &= (-\gamma/2 + i\delta)\rho_{12} + i\Omega^*(\rho_{22} - \rho_{11}) \\
\frac{\partial\rho_{21}}{\partial t} &= -\gamma/2 - i\delta)\rho_{21} - i\Omega(\rho_{22} - \rho_{11}) \\
\frac{\partial(\rho_{22} - \rho_{11})}{\partial t} &= 2i\Omega\rho_{12} - 2i\Omega^*\rho_{21} - \gamma(\rho_{22} - \rho_{11}) - \gamma
\end{aligned} \tag{5}$$

where γ is the dephasing rate and ρ_{ij} are the density operator matrix elements. The dissipation processes are described through operator L_ρ which in the Linblad form becomes [35]

$$L_\rho = \frac{\gamma}{2}[2\sigma_{12}\rho\sigma_{21} - \sigma_{22}\rho - \rho\sigma_{22}] \tag{6}$$

If we define the vector $U(t) = [\rho_{21}(t), \rho_{12}(t), \rho_z(t)]^T$, where superscript T stands for transpose, then we can write Eq. (5) in matrix form

$$\frac{d}{dt}U(t) = MU(t) + B \tag{7}$$

with M being an (3×3) matrix and B a column vector whose elements can be determined from Eq. (5). Steady-state values for populations are derived through $U(\infty) = M^{-1}(-B)$.

Now we are interested in determining the spectral properties of the fluorescent photons in particular resonance fluorescent spectrum (RFS) of the QD. In the steady-state regime, this spectrum is proportional to the Fourier transformation of the correlation function $\lim_{t\to\infty}\langle E_s^-(r, t' + t) \cdot E_s^+(r, t)\rangle$, where $E_s^-(r, t)/E_s^+(r, t)$ is the negative/positive frequency part of the radiation field in the far zone [36]. Therefore, the steady-state RFS can be expressed in terms of the correlation function

$$S(\omega) = Re\left[\lim_{t\to\infty}\int_0^\infty \langle E_s^-(t' + t) \cdot E_s^+(t)\rangle e^{-i(\omega-\omega_L)t'}dt'\right] \tag{8}$$

where $Re[\,]$ denotes the real part of the magnitude enclosed in square brackets, and $E_s^-(t)$ is the negative frequency part of the fluorescent field which in the far-field zone ($|\vec{r}| \gg c/\omega_{21}$) becomes

$$\vec{E}_s^-(\vec{r}, t) = \left[\frac{\omega_{21}^2}{c^2|\vec{r}|}\mu_{12}\sigma_{21}(t - |\vec{r}|/c)\right]e^{i\omega_L(t-r/c)} \tag{9}$$

where μ_{12} is transition dipole moment and $E_s^+(t) = \left(E_s^-(t)\right)^\dagger$. The calculation of $S(\omega)$ requires to evaluate two-time correlation functions, which can be performed by means of the quantum-regression theorem. In addition by using an appropriate unitary transformation via diagonalization matrix, U_{diag}, it is possible to find $S(\omega)$ in the dressed state representation. Since in the dressed state picture it is possible to find peak positions and their width more accurate, we have calculated $S(\omega)$ in the dressed states $|+\rangle, |-\rangle$ with similar procedure as the bare states. The formalism is not presented here for the sake of brevity [37].