Efficiently tunable photon emission from an optically driven artificial molecule

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Efficiently tunable photon emission from an optically driven artificial molecule

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Abstract. In this work, the emission properties of double quantum dots driven by an intense monochromatic electromagnetic field, while undergoing resonant tunneling, are investigated. We find the optically active energy transitions and their corresponding emission intensity, and compute resonance fluorescence spectra for different detunings between the direct and indirect exciton energies. The simulated emission exhibit either three, five, or seven peaks, tunable on demand. On the basis of the obtained results, our proposal offers efficient control of the resonance fluorescence of an artificial molecule, suitable for optoelectronic applications.

1. Introduction
Quantum dots (QDs) are semiconductor heterostructures at the nanometric scale, in which electrons and holes are confined in all three special dimensions and energy states are fully discretized [1]. This discretization yields optical properties well known in atoms such as single photon emission and Rabi oscillations [2,3]. In particular, the distinctive feature of a strongly radiation-matter system so-called Mollow triplet [4], has been successfully observed in QDs [5].

On the other hand, controllable coupling between neighboring QDs has been experimentally achieved by means of electric fields [6]; Hence, interacting double dots are often referred as quantum dot molecules (QDM) [7].

In this work, we propose to combine the advantages of solid emitters for realizing strong radiation matter coupling, with the tunability provided by the additional degree of freedom in double DQs, to form a photonic system in which the number of optical channels can be efficiently adjusted.

2. System and basis
The studied system consist of two QDs coupled by resonant tunneling, interacting with intense radiation from a monochromatic coherent source. This is schematically represented for an InAs/GaAs QDM in figure 1(a), where \( \Delta \) stands for the energy difference between direct and indirect exciton states (Coulomb interaction neglected, \( E_{XD} - E_{XI} = \Delta \)).
In the non-interacting QDM-radiation basis (bare states), three states form the \( n \)-th rung of the Jaynes-Cummings (JC) ladder: the ground QDM state with \( n \) photons \((|n, g\rangle)\), direct exciton state with \( n - 1 \) photons \((|n - 1, XD\rangle)\) and indirect exciton state with \( n - 1 \) photons \((|n - 1, XI]\rangle)\), whose energies are \( E_{n,g}, E_{n-1,XD}, \) and \( E_{n-1,XI}\), respectively. The energies of the bare and dressed states are schematically shown in figure 2(a), for the case in which the monochromatic mode (frequency \( \omega_L \)) is out of resonance respect to the direct and indirect excitons \((\hbar \omega_L - E_{XD} = \Delta_{L-D})\).

![Figure 1](image.png)

**Figure 1.** Considered basis. a) Ground state of the system with \( n \) photons; b) Direct exciton and \( n - 1 \) photons; c) Indirect exciton and \( n - 1 \) photons.

Then, the total Hamiltonian is given by

\[
\hat{H}_T = \hat{H}_M + \hat{H}_R + \hat{H}_{M-R} + \hat{H}_t,
\]

where for each rung, the free QDM Hamiltonian is

\[
\hat{H}_M^n = E_{XD}|n - 1, XD\rangle\langle n - 1, XD| + E_{XI}|n - 1, XI\rangle\langle n - 1, XI| + E_0|n, g\rangle\langle n, g|,
\]

the free-radiation Hamiltonian is

\[
\hat{H}_R^n = (n - 1)\hbar \omega_L|n - 1, XD\rangle\langle n - 1, XD| + (n - 1)\hbar \omega_L|n - 1, XI\rangle\langle n - 1, XI| + n\hbar \omega_L|n, g\rangle\langle n, g|,
\]

the QDM-radiation interaction term is

\[
\hat{H}_{M-R}^n = g\sqrt{n}|n, g\rangle\langle n - 1, XD| + g\sqrt{n}|n - 1, XI\rangle\langle n, g|,
\]

and the interdot tunneling term is

\[
\hat{H}_t^n = t|n - 1, XD\rangle\langle n - 1, XI| + t|n - 1, XI\rangle\langle n - 1, XD|.
\]

Thus, the Hamiltonian for each of the subspaces is analytically diagonalizable and the dressed states can be obtained. These new eigenvectors are superpositions of the bare states, and the oscillator strengths for the allowed transitions are found in terms of the superposition coefficients

\[
C_{i,j}^n = \langle (n - 1), i| (n - 1), j \rangle,
\]

where \( i = g, XD, XI \) and \( j = 1, 2, 3 \).

For a given average number of photons \( m \) in the mode \((m = \langle \hat{N} \rangle)\), set by the driving laser power; the transition energies \( \Delta E_{i,j}^m, (g, t, \Delta_{L-D}, \Delta) \equiv E_j^m - E_{i}^{m-1} \), and the superposition coefficients \( C_{i,j}^m (g, t, \Delta_{L-D}, \Delta) \), depend on the four open parameters of our model, providing a promising scenario for flexible control of emission frequencies.
3. Resonance fluorescence spectra

Setting constant values for the parameters $g\sqrt{m}, t, \Delta_{L-D}$ (10 meV, 10 meV, and 0, respectively) [8,9], we simulate the resonance fluorescence (RF) spectra from the QDM for different values of the tunable parameter $\Delta$. In figures 3a), b), and c) the emission spectra for different values of $\Delta$ are shown, and an interesting on-demand triplet-pentaplet-heptaplet optical transition can be clearly observed.

![Figure 3. RF spectra from a driven QDM for a) $\Delta > 1 eV$, b) $\Delta = 0$, and $\Delta = 0.014 eV$.](image)

In this model, effective tuning of $\Delta$ may be accomplished by increasing the indirect exciton energy through an external bias field, applied in the coupling direction of the QDM [6].

In conclusion, the resonance fluorescence of a quantum dot molecule driven by an intense laser, have been studied, and the predicted triplet-pentaplet-heptaplet transition appears as a convenient scenario for efficient control of optically active frequencies.

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References

[9] A direct exciton radiative linewidth of 200 $\mu$eV, was used in the calculations.