Electrodynamic interactions between a mesoparticle and a quantum dot

Valeri Lozovski\textsuperscript{1,2} and Andrew Tsykhonya\textsuperscript{2,*}

\textsuperscript{1}Institute of High Technologies, T. Shevchenko National University of Kyiv, Volodymirska 64, 01601 Kyiv, Ukraine
\textsuperscript{2}V. Lashkari Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, Nauki Avenue 45, 03028 Kyiv, Ukraine
*Corresponding author: andrew.tsykhonya@gmail.com

Received August 10, 2010; revised November 6, 2010; accepted December 1, 2010; published December 1, 2010 (Doc. ID 133157); published February 3, 2011

We present a self-consistent approach based on Green’s function formalism allowing us to calculate local electromagnetic properties of a complex system consisting of a single-electron spherical quantum dot (QD) interacting with a dielectric mesoparticle. The cases of static and frequency dependent dielectric permittivity of the mesoparticle were considered. In the static case, due to the coupling between the QD and the mesoparticle, the absorption spectrum of the QD gets redshifted. In the frequency dependent case, the absorption line splits into two peaks. The strongest splitting was observed when the resonance frequency of the mesoparticle is close to the transition frequency of the QD. The interaction effects depend on the polarization of the incident light and diminish with increasing of the interparticle distance. © 2011 Optical Society of America

\textit{OCIS codes:} 230.5590, 260.2710, 260.2110.

1. INTRODUCTION

The interest in the electromagnetic properties of quantum dots (QDs) is increasing with the development of nanotechnology. QDs are unique objects characterized by the confinement of an electron in all spatial directions. Independently of the fabrication methods [1–6], QDs are located in the vicinity of the surfaces, microscopic probes, or near other QDs and/or mesoparticles. This implies that QDs can be exposed to a strongly inhomogeneous electromagnetic field resulting in a modification of the optical properties of QDs such as shift, broadening, or splitting of an absorption profile.

In this respect, there has been extensive theoretical and experimental work on interactions of QDs with neighboring objects. For example, in a system of coupled QDs, Coulomb blockade effects [7,8], appearance of magnetization [9], the quantum-gate mechanism [10], as well as formation of delocalized “molecular states” [11,12] have already been reported. Generation and amplification of optical excitations have been realized with QDs coupled to the surface plasmon polaritons in planar structures [13,14] and in metallic nanowires [15]. Optical properties of complex systems, such as QDs incorporated inside nanowires [16], photonic and polaritonic crystals [17–19], or QDs in the vicinity of semiconductor microcavities (microspheres, microdisks) [20–27] have been studied. In this respect, strong coupling effects are evidenced via appearance of transparent and absorbing states and via significant changes in spontaneous emission or photoluminescence spectra. Furthermore, the influence of localized surface plasmons on the energy transfer between semiconductor QDs has been investigated [28–31], and the enhancement of photoluminescence lifetime and its dependence on the distance between QDs and the nanoparticle have been shown.

In spite of the great number of experimental and theoretical works devoted to interaction of QDs with surrounding objects, an important aspect of near-field electrodynamic interactions has not yet been investigated in full. Therefore, in this work, we performed a theoretical description of the local-field effects and nonlocal interactions in a system consisting of a QD and a mesoparticle. The term “mesoparticle” refers to an object with linear dimensions that are much smaller than the wavelength of the probing field. The model gives insight into the optical properties of the system “QD–mesoparticle” and also allows the design of structures with desired properties.

2. LINEAR RESPONSE TO THE LOCAL AND EXTERNAL FIELDS

Modern electrodynamics deals with objects that are small compared to the wavelength of external light. Therefore, the distinction between local and external fields is essential. Let the external long-range field $\mathbf{E}^{(0)}(\mathbf{R}, \omega)$ act on a bulk homogeneous nondispersive nonmagnetic medium. In this case, the local field, $\mathbf{E}(\mathbf{R}, \omega)$, differs from the external one, $\mathbf{E}^{(0)}(\mathbf{R}, \omega)$, by the dielectric constant $\varepsilon(\omega)$:

$$\mathbf{E}(\mathbf{R}, \omega) = \varepsilon(\omega)\mathbf{E}^{(0)}(\mathbf{R}, \omega).$$

The dielectric constant $\varepsilon(\omega)$ reveals enhancement or attenuation of the external field in the bulk. In contrast, when a mesoparticle is exposed to a long-range external field, the local field could be strongly inhomogeneous as the near-surface transition layer is an essential part of the particle volume. In this case, the relation between the local and the external fields cannot be represented in the simple form of Eq. (1). Therefore, the effective susceptibility method was suggested [32]. In this method, the relation connecting the local current density, $j_i(\mathbf{R}, \omega)$, with the external field in the frame of effective susceptibility formalism is

$$j_i(\mathbf{R}, \omega) = -i\omega X_{ij}(\mathbf{R}, \omega)\mathbf{E}_j^{(0)}(\mathbf{R}, \omega).$$
where $X_{ij}(\mathbf{R}, \omega)$ is the effective susceptibility, the linear response to the external field. This expression already contains information about nonlocal electrodynamic interactions that determine the behavior of the system. As a result, knowledge of the effective susceptibility allows finding the local field at any point in the system [32].

3. FORMULATION OF THE PROBLEM

We are aiming to consider local-field effects in a system of a QD and a mesoparticle exposed to an external long-range field $\mathbf{E}^{(0)}(\mathbf{R}, \omega)$. Both particles are of spherical shape with the radii $R_{\text{QD}}$ and $R_{\text{MP}}$ of the QD and the mesoparticle, respectively. The particles are embedded in an infinitely large dielectric medium with the dielectric constant $\varepsilon_m$. The electrodynamic properties of the medium are characterized by its Green’s function, $G_{ik}(\mathbf{R}, \mathbf{R}', \omega)$. The origin point of the Cartesian coordinate system is located in the center of the QD; the centers of both particles are on the OZ axis and $d$ is the distance between particle surfaces along the OZ axis (Fig. 1). The total field acting on both particles differs from the external field $\mathbf{E}^{(0)}(\mathbf{R}, \omega)$. Indeed, the field acting on the QD consists of two parts: the external one $\mathbf{E}^{(0)}(\mathbf{R}, \omega)$ and the field reradiated by the mesoparticle. On the other hand, the field affecting the mesoparticle consists of the external field $\mathbf{E}^{(0)}(\mathbf{R}, \omega)$ and the field reradiated by the QD. To calculate the effective susceptibilities of the QD and mesoparticle, a relation between the external and the local field has to be established.

4. RELATION BETWEEN THE EXTERNAL AND THE LOCAL FIELD

The equation connecting the local field and local currents induced by the external field inside the QD is the Lippmann–Schwinger equation [32–34]:

$$E_i(\mathbf{R}, \omega) = \hat{E}^{(0)}_i(\mathbf{R}, \omega) - i\mu_0v_0 \int_{V_{\text{QD}}} d\mathbf{R}' G_{ik}(\mathbf{R}, \mathbf{R}', \omega) j_k(\mathbf{R}', \omega),$$

where $G_{ik}(\mathbf{R}, \mathbf{R}', \omega)$ is the Green’s function of the medium in which the QD is embedded, $V_{\text{QD}}$ is the volume of the QD, and $\hat{E}^{(0)}_i(\mathbf{R}, \omega)$ is the field acting on the QD and consisting of the probing field and the field scattered by the spherical mesoparticle and can be written as [35]

$$\hat{E}^{(0)}_i(\mathbf{R}, \omega) = E^{(0)}_i(\mathbf{R}, \omega) - \frac{X^{(\text{MP})}}{\omega} \left( E^{(0)}(\mathbf{R}, \omega) \left( \frac{R_{\text{MP}}}{R} \right)^3 - R_{\text{MP}} \left( \frac{E^{(0)}(\mathbf{R}, \omega) \cdot \mathbf{R}}{R^5} \right) \right) = \frac{T^{(0)}}{\omega}(\mathbf{R}, \omega) E^{(0)}(\mathbf{R}, \omega),$$

where $X^{(\text{MP})}$ is the effective susceptibility of the mesoparticle. In Eq. (4), $T^{(0)}(\mathbf{R}, \omega)$ is the scattering matrix of the mesoparticle.

Furthermore, the current density $j_k(\mathbf{R}, \omega)$ in the integrand of Eq. (3) is nonlocally connected with the local field $E_k(\mathbf{R}', \omega)$ inside the QD via the conductivity tensor $\sigma_{ik}(\mathbf{R}, \mathbf{R}', \omega)$:

$$j_k(\mathbf{R}, \omega) = \int_{V_{\text{QD}}} d\mathbf{R}' \sigma_{ik}(\mathbf{R}, \mathbf{R}', \omega) E_i(\mathbf{R}', \omega).$$

The conductivity is determined by electron transition currents $j^{(\alpha)}_k(\mathbf{R})$ between the states $\alpha$ and $\beta$ [33–36]:

$$\sigma_{ik}(\mathbf{R}, \mathbf{R}', \omega) = \frac{1}{i\omega} \sum_a a_a(\omega) j^{(\alpha)}_k(\mathbf{R}) \delta(\mathbf{R}') \delta(\mathbf{R}),$$

with

$$a_a(\omega) = 2\hbar \frac{E_a - E_0}{(E_a - E_0)^2 - \hbar^2 (\omega + i\nu)^2}.$$ 

Here, $E_a$ is the energy of an $\alpha$ electron state, and $\nu$ is a damping constant. Then Eq. (3) for the self-consistent local field can be written in the form

$$E_i(\mathbf{R}, \omega) = \hat{E}^{(0)}_i(\mathbf{R}, \omega) - \sum_a a_a(\omega) F_i(\mathbf{R}, \omega) \int_{V_{\text{QD}}} d\mathbf{R}' G_{ik}(\mathbf{R}, \mathbf{R}', \omega) j^{(\alpha)}_k(\mathbf{R}'),$$

where

$$F_i(\mathbf{R}, \omega) = \mu_0 \int_{V_{\text{QD}}} d\mathbf{R}' G_{ik}(\mathbf{R}, \mathbf{R}', \omega) j^{(\beta)}_k(\mathbf{R}').$$

Following [36], the integral Eq. (8) can be rewritten as a set of algebraic equations:

$$\gamma_{ij}(\omega) = \gamma_{ij}^{(0)}(\omega) - \sum_a a_a(\omega) N_{ij}^{(\alpha)}(\omega) \gamma_{\alpha i}(\omega),$$

with

$$\gamma_{ij}^{(0)}(\omega) = \int_{V_{\text{QD}}} d\mathbf{R} j^{(\alpha)}_j(\mathbf{R}) E_i(\mathbf{R}, \omega),$$

$$\gamma_{ij}^{(\alpha)}(\omega) = \int_{V_{\text{QD}}} d\mathbf{R} j^{(\beta)}_j(\mathbf{R}) E_i^{(0)}(\mathbf{R}, \omega).$$

Fig. 1. (Color online) Geometry of the system under study.
N^{0\alpha}(\omega) = \mu_0 \int \frac{d\mathbf{R}}{V_{QD}} \int \frac{d\mathbf{R}'}{V_{QD}} G_{ik}^{(0)}(\mathbf{R}, \mathbf{R}') \mathbf{J}_{k}^{\alpha(0)}(\mathbf{R}). \tag{13}

It is important to note that $N^{0\alpha}$ plays the role of the self-energy part of the QD. Because the external field is assumed to be constant on the dimensions of the QD, Eq. (12) can be further rewritten to

\[ \gamma_{(0)}^{\alpha}(\omega) = \int \frac{d\mathbf{R}_{k}}{V_{QD}} T_{kj}^{(0)}(\mathbf{R}, \mathbf{R}') E_{i}^{(0)}(\mathbf{R}, \omega) = \gamma_{j}^{\alpha(0)}(\omega) E_{j}^{(0)}(\mathbf{R}_{0}, \omega). \tag{14} \]

Then, the set of Eqs. (10) can be expressed as

\[ \sum_{\alpha} (\delta_{\alpha\beta} + a_{\alpha}(\omega) N^{0\alpha}(\omega)) \gamma_{\beta}(\omega) = \gamma_{j}^{\alpha(0)}(\omega) E_{j}^{(0)}(\mathbf{R}_{0}, \omega). \tag{15} \]

The solution of these algebraic equations has the form

\[ \gamma_{\beta}(\omega) = B^{\beta\alpha}_0 \Delta^{-1} \gamma_{j}^{\alpha(0)}(\omega) E_{j}^{(0)}(\mathbf{R}_{0}, \omega), \tag{16} \]

where $B^{\beta\alpha}_0$ is the relevant algebraic complement and $\Delta$ is the determinant of the matrix $(\delta_{\alpha\beta} + a_{\alpha}(\omega) N^{0\alpha}(\omega))$. Once the set of the algebraic equations is solved, the relation between local and external fields takes the form

\[ E_{j}(\mathbf{R}, \omega) = \Lambda_{ij}(\mathbf{R}, \omega) E_{j}^{(0)}(\mathbf{R}, \omega), \tag{17} \]

with a local-field factor

\[ \Lambda_{ij}(\mathbf{R}, \omega) = \left\{ T_{ij}^{(0)}(\mathbf{R}, \omega) - \sum_{\alpha, \beta} a_{\alpha}(\omega) F_{i}^{(0)}(\mathbf{R}, \omega) \frac{B^{\beta\alpha}_0}{\Delta} \gamma_{j}^{\alpha(0)}(\omega) \right\}. \tag{18} \]

In the frame of the pseudovacuum Green’s function formalism \cite{22}, the Green’s function of the system “vacuum+mesoscopic” can be written as

\[ G_{ij}(\mathbf{R}, \mathbf{R'}, \omega) = G_{ij}^{(0)}(\mathbf{R}, \mathbf{R'}) - k_0^2 \int \frac{d\mathbf{R}'}{V_{QD}} G_{ik}^{(0)}(\mathbf{R}, \mathbf{R'}) \times X_{kl}^{(3MP)}(\mathbf{R}'', \omega) G_{lj}^{(0)}(\mathbf{R}'', \mathbf{R}'), \tag{19} \]

where $G_{ij}^{(0)}(\mathbf{R}, \mathbf{R'})$ is the electrodynamic Green’s function of the matrix and $k_0 = \omega/c$ ($c$ is light velocity in vacuum). Since, the effective susceptibility of a spherical mesoparticle does not depend on the coordinates \cite{35,37}, the self-energy part $N^{\alpha}(\omega)$ can be rewritten as the sum

\[ N^{\alpha}(\omega) = N_{0}^{\alpha} - N_{ex}^{\alpha}(\omega), \tag{20} \]

where

\[ N_{0}^{\alpha} = \mu_0 \int \frac{d\mathbf{R}}{V_{QD}} \int \frac{d\mathbf{R}'}{V_{QD}} G_{ik}^{(0)}(\mathbf{R}, \mathbf{R'}) \mathbf{J}_{k}^{\alpha(0)}(\mathbf{R}). \tag{21} \]

N_{ex}^{\alpha}(\omega) = k_0^2 \mu_0 X_{kl}^{(3MP)}(\omega) \int \frac{d\mathbf{R}'}{V_{QD}} \int \frac{d\mathbf{R}''}{V_{QD}} \left\{ \int \frac{d\mathbf{R}_{j}^{(0)}(\mathbf{R}) G_{ij}^{(0)}(\mathbf{R}, \mathbf{R}') \right\} \times \left\{ \int \frac{d\mathbf{R}_{j}^{(0)}(\mathbf{R}) G_{ij}^{(0)}(\mathbf{R}, \mathbf{R}') \right\} \tag{22} \]

reveals the contribution to the self-energy part caused by the interaction between the QD and the mesoparticle.

5. ABSORPTION OF ELECTROMAGNETIC FIELD BY THE QD

To calculate the energy absorbed by the QD, the dissipative function $Q(\omega)$ is defined as Joule heat absorbed by unit volume of the QD per unit time. After time averaging, the dissipative function can be written in the form \cite{35}

\[ Q(\omega) = \langle E_{i}(\mathbf{R}, \omega) J_{i}(\mathbf{R}, \omega) + E_{j}(\mathbf{R}, \omega) J_{j}(\mathbf{R}, \omega) \rangle. \tag{23} \]

Here $(\ldots)$ means averaging over particle volume. Using Eqs. (5) and (17), one can rewrite this equation as follows:

\[ Q(\omega) = \left\langle \Lambda_{ij}(\mathbf{R}, \omega) E_{i}^{(0)}(\mathbf{R}, \omega) \right\rangle \times \int \frac{d\mathbf{R}' \sigma_{ij}(\mathbf{R}, \mathbf{R}', \omega) L_{ik}(\mathbf{R}, \omega) E_{k}^{(0)}(\mathbf{R}', \omega) \right\rangle \]

\[ + \left\langle \Lambda_{ij}(\mathbf{R}, \omega) E_{i}^{(0)}(\mathbf{R}, \omega) \right\rangle \times \int \frac{d\mathbf{R}' \sigma_{ij}(\mathbf{R}, \mathbf{R}', \omega) L_{ik}(\mathbf{R}, \omega) E_{k}^{(0)}(\mathbf{R}', \omega) \right\rangle \}. \tag{24} \]

Taking into account that amplitude of the external field changes slowly along the QD and interchanging the indices in the second term of Eq. (24), using Eqs. (5) and (18), the dissipative function $Q(\omega)$ takes the form

\[ Q(\omega) = \frac{1}{i \omega V_{QD}} \left( \int \frac{d\mathbf{R}'_{ik}(\mathbf{R}) \left\{ T_{ij}^{(0)}(\mathbf{R}, \omega) \right\}}{V_{QD}} \right. \]

\[ - \sum_{\delta} a_{\delta}(\omega) F_{\delta}^{i}(\mathbf{R}, \omega) \frac{B^{\delta\alpha}_0}{\Delta} \gamma_{j}^{\alpha(0)}(\omega) \}

\[ \times \int \frac{d\mathbf{R}' \sigma_{\delta ij}(\mathbf{R}, \mathbf{R}', \omega) L_{ik}(\mathbf{R}, \omega) E_{k}^{(0)}(\mathbf{R}', \omega) \right\rangle \]

\[ - \sum_{\delta} a_{\delta}(\omega) F_{\delta}^{i}(\mathbf{R}, \omega) \frac{B^{\delta\alpha}_0}{\Delta} \gamma_{j}^{\alpha(0)}(\omega) \}

\[ \times \int \frac{d\mathbf{R}' a_{\delta}(\omega) \bar{f}_{\delta j}(\mathbf{R}') \left\{ T_{ij}^{(0)}(\mathbf{R}, \omega) \right\}}{V_{QD}} \]

\[ - \sum_{\delta} a_{\delta}(\omega) F_{\delta}^{i}(\mathbf{R}, \omega) \frac{B^{\delta\alpha}_0}{\Delta} \gamma_{j}^{\alpha(0)}(\omega) \}

\[ \times \int \frac{d\mathbf{R}' a_{\delta}(\omega) \bar{f}_{\delta j}(\mathbf{R}') \left\{ T_{ij}^{(0)}(\mathbf{R}, \omega) \right\}}{V_{QD}} \] \tag{25} \]

Furthermore, taking into account the relations $T_{ij}^{(0)}(\mathbf{R}) = \bar{J}_{j}^{(0)}(\mathbf{R})$, $\int_{V_{QD}} d\mathbf{R}' \bar{J}_{ij}^{(0)}(\mathbf{R}) T_{ij}^{(0)}(\mathbf{R}, \omega) = \bar{J}_{i}^{(0)}(\omega)$, $\int_{V_{QD}} d\mathbf{R}' f_{ij}^{(0)}(\mathbf{R}) F_{ij}^{(0)}(\mathbf{R})$. \tag{25}
\[ Q(\omega) = \frac{1}{2} \mathcal{V}_{\text{QD}} \text{Im} \alpha_{\omega}(\omega - \sum_{\delta} a_{\delta}(\omega) N_{\delta}(\omega) \frac{\mathcal{P}_{\delta}}{\Delta} \gamma_{\delta}(\omega))^\dagger \] 

\times \left\{ \gamma_{\delta}(\omega) - \sum_{\delta} a_{\delta}(\omega) N_{\delta}(\omega) \frac{\mathcal{P}_{\delta}}{\Delta} \gamma_{\delta}(\omega) \right\} E_k^{(0)}(E_j^{(0)})^\dagger. \tag{26} \]

Equation (26) determines the energy that is dissipated by the QD only. To find the absorption of the entire system consisting of a QD and a mesoparticle, Eq. (25) has to be applied to both particles.

6. NUMERICAL CALCULATIONS

A. System Under Study

Numerical calculations were performed for a single-electron QD with isotropic parabolic confinement potential

\[ U(r) = - \frac{m^* e_0^2}{2} r^2, \tag{27} \]

where \( m^* \) is the effective mass of the electron in the QD and \( e_0 \) is the characteristic frequency. In this case, according to \[ \text{[28], the energy levels of the QD can be described by the expression} \]

\[ E_{\text{amp}} = \hbar \omega_0 \left( n + m + p + \frac{3}{2} \right). \tag{28} \]

where \( n, m, \) and \( p \) are the main quantum numbers of the electron moving along the axes \( OX, OY, \) and \( OZ, \) respectively. For numerical calculations, the parameters of a GaAs QD were chosen: \( \omega_0 = 40 \) meV, \( m^* = 0.068 \times m_0, \) \( m_0 \) is the free electron mass, and \( \nu = 0.01 \times \omega_0. \) Limiting consideration to the two-level QD, the electron transition current between the ground and the first excited level can be written as \[ \text{[38]} \]

\[ J^{(0)}(R) = c_1 \exp(-\beta^2 R^2), \tag{29} \]

with \( \beta = (m^{*} \omega_0^2)^{1/2} \) and \( c_1 = \frac{\hbar e_0^{1/2}}{1 \cdot \sqrt{2 \pi} m^{*} e_0}. \) The QD and the mesoparticle are assumed to be in a dielectric matrix with the dielectric constant \( \epsilon_m = 2.5. \)

B. Mesoparticle with Static Permittivity

In the following, the optical properties of a system consisting of a QD and a dielectric mesoparticle with static permittivity

\( \epsilon_p = 12 \) are considered. The radii of the QD and mesoparticle are equal to \( R_{\text{QD}} = 11 \) nm and \( R_{\text{MP}} = 30 \) nm, respectively. Absorption spectra of the QD for different interparticle distances \( d \) and polarizations of the incident light are shown in Fig. 2.

Please note that, when the interparticle distance \( d \) is large \( (d > 60 \) nm), absorption lines approach the spectrum of a single QD. For small interparticle distances \( (d < 40 \) nm), interaction between particles is rather strong, resulting in a redshift of the absorption line and in a modification of its intensity. For \( x \)-polarization of the incident light, intensity of the absorption line decreases with increase of the interparticle distance \[ \text{[Fig. 2(a)]}, \] while for \( z \)-polarization, increase of intensity is observed when the distance \( d \) increases \[ \text{[Fig. 2(b)].} \] The behavior of the absorption spectra for different polarizations of the incident light can be explained in the following way: under action of an \( x \)-polarized electromagnetic wave, the QD is located in the region of the strong and highly inhomogeneous local field \[ \text{[Fig. 3].} \] When the distance between the particles decreases, the local field becomes stronger, leading to a stronger interaction between the QD and the mesoparticle. As a consequence, enhancement of the energy absorption is observed. In contrast, in the case of a \( z \)-polarized electromagnetic wave, the QD is in the region of the weak local field, which causes a decrease of the absorption intensity.

The modification of the absorption spectra of the QD on the radius of a mesoparticle is shown in Fig. 4. The interaction between the QD and the mesoparticle is found to be stronger for mesoparticles of bigger radii. This finding can be explained by using Eq. (4). The amplitude of the scattered field \( \mathcal{E}^{(0)}(R, \omega) \) in the point \( R \) is dependent on the radius of the mesoparticle

\[ \mathcal{E}^{(0)}(R, \omega) \sim \left( \frac{R_{\text{MP}}}{R} \right)^3. \tag{30} \]

In this respect, the scattered field in the center of the QD can be written

\[ \mathcal{E}^{(0)}(R_{\text{QD}}, \omega) \sim \left( \frac{R_{\text{MP}}}{R_{\text{MP}} + d + R_{\text{QD}}} \right)^3 = \left( \frac{1}{1 + (d + R_{\text{QD}})/R_{\text{MP}}} \right)^3, \tag{31} \]

revealing that the amplitude of the scattered field increases with increasing of the mesoparticle radius.
C. Mesoparticle with Frequency-Dependent Permittivity

Here we concentrate on the case when permittivity of the material of the mesoparticle exhibits resonance properties:

\[ \varepsilon_p(\omega) = \varepsilon_\infty \frac{\omega_{LO}^2 - \omega^2}{\omega_{TO}^2 - \omega^2 - i\gamma\omega}, \]

where \( \varepsilon_\infty \) is the high-frequency permittivity, \( \gamma \) is the damping parameter, and \( \omega_{LO} \) and \( \omega_{TO} \) are the frequencies of the longitudinal and transversal optical phonons, respectively. The following values of the parameters were chosen for the calculations: \( \varepsilon_\infty = 12 \), \( \omega_{LO} = 1.1 \times \omega_0 \), \( \gamma = 0.01 \times \omega_0 \), \( \omega_0 = 40 \) meV, and the radii of the QD and the mesoparticle are \( R_{\text{QD}} = 11 \) nm, \( R_{\text{MP}} = 30 \) nm, respectively. The frequency of transversal optical phonon \( \omega_{TO} \) was varied in the range of \((0.5...0.9) \times \omega_0\).

Absorption spectra of the QD for different frequencies of the transverse optical phonon \( \omega_{TO} \) and for fixed interparticle distance \( d = 11 \) nm are shown in Fig. 5. In this case, the localized excitation (usually named the localized surface plasmon polariton) is supported by the mesoparticle. The coupling between the QD and the localized excitation leads to the splitting of the absorption spectrum into two peaks and to the modification of the absorption intensity. The changes are maximal when the optical phonon frequency \( \omega_{TO} \) reaches \( 0.7 \times \omega_0 \), which corresponds to the situation when the resonance frequency of the mesoparticle is close to the transition frequency \( \omega_0 \) of the QD. The splitting of the absorption line is observed clearly just in the resonance case and it strongly depends on the interparticle distance. As in the case of the static permittivity of the mesoparticle, the interactions quickly diminish with increase of the distance between the particles, and vanish when the interparticle distance exceeds 5 QD radii. Absorption spectra reveal the same dependence on the polarization of the external field as in the previous case of the static permittivity of the mesoparticle.

7. SUMMARY AND DISCUSSION

In real systems, QDs are located in the vicinity of other objects, i.e., mesoparticles, and thus they experience not only an applied external electromagnetic field but also an inhomogeneous field scattered from the neighboring objects. The modification of the optical properties of a QD caused by presence of a dielectric spherical mesoparticle was investigated in the present work. It was shown that interaction between a
a. Permittivity of the mesoparticle does not depend on the frequency. In this case, interaction of a QD with a mesoparticle leads to a redshift of the absorption line. These changes nonlinearly depend on the distance between the particles and quickly vanish when the distance approaches 3–5 QD radii. As a result of interactions between the QD and the mesoparticle, absorption spectra reveal a dependence on the polarization of the incident light: for an x-polarized field, an enhancement, and for z-polarization, a decrease, of the absorption intensity was observed.

b. Frequency-dependent permittivity of the mesoparticle. Coupling between a QD and a mesoparticle leads to splitting of the absorption profile. The strongest influence is observed when the resonance frequency of the mesoparticle (excitation frequency of the so-called localized surface plasmon polariton) is close to the transition frequency of the QD. This finding is in agreement with the earlier study by Komarala et al. [39], where the authors investigated localized surface plasmon enhanced photoluminescence (PL) from QDs on monolayers of nanoparticles. It was shown that, in the off-resonance case, coupling results in a redshift and broadening of the luminescence spectrum, as well as an increase of the PL rate. However, no change in intensity and PL rate was observed in the resonance case [39]. This observation is rather surprising as it was experimentally demonstrated [29–31] that the strongest enhancement of the PL and the energy transfer efficiency takes place under resonance conditions, when localized surface plasmons are excited. Furthermore, thorough quantum-mechanical investigations of complex systems consisting of QDs embedded in nanowires, polaritonic, and photonic crystals were performed [16–19]. The study predicts a modification of the optical properties of the systems, i.e., absorption line splitting and shifting, and the appearance of transparency states in the absorption profile caused by the strong coupling between QD states and cavity modes of the host media.

In addition, it is important to emphasize that, in the current work, we considered a relatively simple case of a single-electron QD with isotropic parabolic confinement potential [40]. However, the developed theory can be extended to the nonparabolic and anisotropic confinement potentials, as well as to the cases of several localized electrons [41,42].

REFERENCES


38. V. V. Mitin, V. A. Kochelap, and M. A. Stroscio, Quantum Heterostructures. Microelectronics and Optoelectronics (Cambridge University, 1999).


