The intensity of the plasmon-exciton of three spherical metal nanoparticles on the semiconductor quantum dot having three external fields

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The intensity of the plasmon-exciton of three spherical metal nanoparticles on the semiconductor quantum dot having three external fields

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Abstract

The influence of the plasmonic of three spherical metal nanoparticles (MNPs) on the semiconductor quantum dot (SQD) having three external fields, is analyzed. The density matrix equations are modified for the description of the optical properties of the SQD-MNPs nanosystem. We study theoretically the role of the plasmon-exciton dipole coupling in the SQD-MNPs nanosystem. We investigate the dependence of the plasmon-exciton dipole coupling of the SQD-MNPs nanosystem on the position of three spherical MNPs with respect to SQD as well as on the material parameters of the hybrid nanosystem. The direction and detunings of the three external fields play an important role on the characterization of the SQD-MNPs nanosystem.

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1 Introduction:

The optical properties of complex nanosystems, that when a semiconductor quantum dot (SQD) is in the vicinity of a metallic nanoparticle (MNP), are the area of considerable current interest. So, the optics of the SQD become strongly sensitive to the structural parameters of the nanosystem, the intensity of the plasmon-exciton dipole coupling and the dielectric constant of the environment when combine semiconductor quantum dot (SQD) and plasmonic nanostructures and hence it carry out in the interdisciplinary applications of nanoscience. The phenomena that have been studied in these research area are the phase control of absorption and dispersion as well complete optical transparency $[1-4]$, Fano effects in energy absorption $[5-8]$, Plasmonic Electromagnetically Induced Transparency (EIT) $[9-12]$, the enhancement of nonlinear Kerr and susceptibilities in several quantum systems $[13-16]$. The terahertz generation enhancement from intraband transition in self-assembled SQD molecules near a (MNP) is discussed in [17]. The investigating of the spatial properties of Coherent-Plasmonic (CP) field and demonstrating how it depends on the collective molecular states of the SQD-MNP system (bright and dark states) is shown in [18, 19] that when the coherent SQD-MNP molecule is in the dark state, i.e., the SQD does not emit light, the CP field is spatially confined around the MNP. It is studied that the states of polarization of coherent plasmonic fields of a SQD-MNP system in the environment surrounding the MNP and investigated how the dynamics of these states were evolved with time when this system was interacting with a time-dependent laser field $[20-22]$. Plasmon-assisted two-photon Rabi oscillations in a semiconductor quantum dot – metal nanoparticle heterodimer is investigated in [23]. The demonstration of multipole effect and the intensity of the plasmon-exciton dipole coupling in the SQD-MNP nanosystem are shown in $[24-27]$.

In this paper, we consider a single SQD in close vicinity to a three spherical MNPs. The present scheme is based on a coupled SQD-MNPs nanosystem in the presence of the pump, control and probe fields. The SQD is taken as a four level V-type system in which the distinct excitonic transitions occur. Theoretically, we will be studying the effect of the plasmon-exciton dipole coupling in the SQD-MNP nanosystem and investigating the dependence of the plasmon-exciton dipole coupling of the SQD-MNP nanosystem on the position of MNPs with a SQD as well as on the material parameters of the hybrid nanosystem. The paper is organized as follows: in Section 2, we describe the SQD-MNP nanosystem, derive the density matrix equations describing the dynamics of the system and obtain the form of the plasmon-exciton dipole coupling for the SQD-MNP nanosystem. In Section 3, we discuss our numerical results. Finally, we present our conclusions in Section 4.

2 Theoretical model and description:

In this paper, we theoretically investigate coherent light-matter interaction in a nano-hybrid between a small size of SQD and three spherical MNP's of different radii R_1, R_2 and R_3. The schematic diagram of the nano-system is considered as a V-type four-level SQD structure. It is composed of four states $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$ with energies $\hbar\omega_1$, $\hbar\omega_2$, $\hbar\omega_3$ and $\hbar\omega_4$, respectively, as illustrated in Fig.1. The nanohybrid structure is subjected to the pump, probe and control fields with amplitudes E_2, E_3 and E_4 and frequencies ν_2, ν_3 and ν_4, respectively. The weak probe field derives the excitonic transition $|1\rangle \leftrightarrow |3\rangle$ with resonance frequency ω_{13}, where $\omega_{nm} = \omega_n - \omega_m$ and $(n, m = 1, 2, 3, 4)$. The pump and control fields derive the excitonic transitions $|1\rangle \leftrightarrow |2\rangle$ and $|3\rangle \leftrightarrow |4\rangle$ with resonance frequencies ω_{12} and ω_{34} respectively. The SQD is situated at center-to-center distance r_1, r_2 and r_3 from the frist, second and third spherical MNP respectively. The distance r_j has an angle θ_j $(j = 1, 2, 3)$ with respect to the $Z-$ *axis* for the frist, second and third spherical MNPs are illustrated in Fig.1, respectively. We consider a frist spherical MNP is postioned at center-to-center distance r_{12} and r_{13} from the second and third spherical MNP respectively, while the second spherical MNP is at center-to-center distance r_{23} from the third spherical MNP. The excitonic transitions for the SQD $|1\rangle \leftrightarrow |2\rangle$, $|1\rangle \leftrightarrow |3\rangle$ and $|3\rangle \leftrightarrow |4\rangle$ are characterized by the transition dipole moments μ_{12} , μ_{13} and μ_{34}, respectively. Where the optical excitations in the SQD are excitons and the oscillating external fields give rise to oscillations of conducting electrons in the MNP's, conventionally called localized surface plasmon (LSP). So, Excitons and Plasmons are excited in the nanohybrid and interact with each other via the dipole-dipole interaction, which give rise to a renormalization of the field experienced by both the SQD and MNP's.The dielectric constant of the SQD is represented by ϵ_s and it is surrounded by a material with dielectric constant ϵ_B. While the three MNPs are treating as a classical dielectric particles with dielectric function $\epsilon_{mj}(\omega)$ and mj is standing for MNP_j where $(j = 1, 2, 3)$. The dielectric function $\epsilon_{m_j}(\omega)$ is obtained for the spherical MNP as [28]:

$$\epsilon_{mj}(\omega) = 1 - \frac{\omega_{pj}^2}{\omega^2 + i\gamma_{bj}\omega}, \qquad (j = 1, 2, 3) \tag{1}$$

where ω_{pj} is the plasma frequency for spherical MNP and γ_{bj} is the damping constant. The Hamiltonian of the nanohybrid system can be expressed as:

$$H_{SQD} \;=\; \hbar \sum_{j=1}^{4} \omega_j \sigma_{jj} - \left[\boldsymbol{\mu}_{12}.\mathbf{E}_{SQD}^2 \sigma_{12} + \boldsymbol{\mu}_{13}.\mathbf{E}_{SQD}^3 \boldsymbol{\sigma}_{13} + \boldsymbol{\mu}_{34}.\mathbf{E}_{SQD}^4 \sigma_{34} + H.C.\right] \tag{2}$$

where $\sigma_{ij} =| i\rangle\langle\ j\ |$ is the dipole transition operator between$| \ i\rangle$ and $\langle\ j\ |$ of the SQD. $\mathbf{E}_{SQD}^i$ $(i = 2, 3, 4)$ are the fields felt by the SQD polarized along the $|\ 1\rangle \iff |\ 2\rangle$, $|\ 1\rangle \iff |\ 3\rangle$ and $|\ 3\rangle \iff |\ 4\rangle$ transitions respectively. So, we have :

$$\mathbf{E}_{SQD}^i = \frac{1}{\varepsilon_{effs}} \left[\mathbf{E}_i + \sum_{j=1}^{3} \mathbf{E}_{SQD}^{ij} \right], \qquad (i = 2, 3, 4) \tag{3}$$

where, $\varepsilon_{effs} = [\frac{\epsilon_s + 2\epsilon_B}{3\epsilon_B}]$ is the screening of the dielectric material of SQD.

Supposing that we have two cases for the direction of the fields $(\mathbf{E}_i)$: the first case (ZZY) that means the direction of the fields $(\mathbf{E}_2, \mathbf{E}_3)$ are along the $Z - axis$ and the field $(\mathbf{E}_4)$ is along the $Y - axis$. The second case (ZYZ): the direction of the fields $(\mathbf{E}_2, \mathbf{E}_4)$ are along the $Z - axis$ and the field $(\mathbf{E}_3)$ is along the $Y - axis$. $\mathbf{E}_{QD}^{ij}$ are the fields on SQD from the three MNPs and given by:

$$\mathbf{E}^{ij}_{SQD} = \frac{1}{4\pi\epsilon_0\epsilon_B r_j^3}\left[3(\mathbf{p}_{ij}.\widehat{\mathbf{r}}_j)\widehat{\mathbf{r}}_j - \mathbf{p}_{ij}\right] \tag{4}$$

where the unite vector $\widehat{\mathbf{r}}_j$ along the vector $\mathbf{r}_j$ is given by:

$$\widehat{\mathbf{r}}_j = \cos\theta_j \widehat{Z} + \sin\theta_j \widehat{Y}, \ \ (j = 1, 2, 3) \tag{5}$$

The vector dipoles $\mathbf{p}_{ij}$ originate from the charge induced on the surface of the MNPs and direct in the $Z - axis$ where is given by:

$$\mathbf{p}_{ij} = \alpha_j \mathbf{E}_{ij},\ \alpha_j = \frac{4\pi\epsilon_0\epsilon_B R_j^3\gamma_j}{\varepsilon_{effm_j}},\ \gamma_j = \frac{\epsilon_{m_j}(\omega) - \epsilon_B}{\epsilon_{mj}(\omega) + 2\epsilon_B} \tag{6}$$

Where, $\mathbf{E}_{ij}$ (for $i = 2, 3, 4$ & $j = 1, 2, 3$) are the fields acting on the three MNPs and given by:

$$\mathbf{E}_{ij} = \frac{1}{\varepsilon_{effm_j}}\left[\mathbf{E}_i + \mathbf{E}^{SQD}_{ij} + \mathbf{E}^{ik}_{ij} + \mathbf{E}^{il}_{ij}\right] \tag{7}$$

where, $\varepsilon_{effm_j} = \frac{\epsilon_{m_j}(\omega)+2\epsilon_B}{3\epsilon_B}$ is the screening of the dielectric material of the three spherical MNPs. $\mathbf{E}^{SQD}_{ij}$ (for $i = 2, 3, 4$ & $j = 1, 2, 3$) are the fields from the SQD on the three MNPs and given by:

$$\mathbf{E}^{SQD}_{ij} = \frac{1}{4\pi\epsilon_0\epsilon_B r_j^3}\left[3(\mathbf{p}^i_{SQD}.\widehat{\mathbf{r}}_j)\widehat{\mathbf{r}}_j - \mathbf{p}^i_{SQD}\right], i = q, 4 \tag{8}$$

$$p^q_{SQD} = \mu_{1q}(\rho_{1q} + \rho_{q1}), \quad q = 2, 3 \tag{9}$$

$$p^4_{SQD} = \mu_{34}(\rho_{34} + \rho_{34}), \qquad i = 4 \tag{10}$$

Also, the fields $\mathbf{E}^{ik}_{ij}$ and $\mathbf{E}^{il}_{ij}$ are resulted to the interaction between every two polarized MNPs for ($j, k, l = 1, 2, 3$ and $j \neq k \neq l, i = 2, 3, 4$) and given by:

$$\mathbf{E}^{ik}_{ij} = \frac{1}{4\pi\epsilon_0\epsilon_B r_{jk}^3}\left[3(\mathbf{p}_{ik}.\widehat{\mathbf{r}}_{jk})\widehat{\mathbf{r}}_{jk} - \mathbf{p}_{ik}\right], \tag{11}$$

$$\mathbf{E}^{il}_{ij} = \frac{1}{4\pi\epsilon_0\epsilon_B r_{jl}^3}\left[3(\mathbf{p}_{il}.\widehat{\mathbf{r}}_{jl})\widehat{\mathbf{r}}_{jl} - \mathbf{p}_{il}\right] \tag{12}$$

Where, $\widehat{\mathbf{r}}_{jk} = \widehat{\mathbf{r}}_k - \widehat{\mathbf{r}}_j$ and $\widehat{\mathbf{r}}_{jl} = \widehat{\mathbf{r}}_l - \widehat{\mathbf{r}}_j$. By introducing $\mathbf{E}^i_{SQD}$ for $(i = 2, 3, 4)$ into Eq. (2), then the total Hamiltonian of the SQD is expressed as:

$$H_{SQD} = \hbar\sum_{j=1}^{4}\omega_j\sigma_{jj} - \hbar\ \Omega^{eff}_2\ \sigma_{12} - \hbar\ \Omega^{eff}_3\ \sigma_{13} - \hbar\ \Omega^{eff}_4\ \sigma_{34} + H.C. \tag{13}$$

where:

$$\Omega_2^{eff} = \left[\Omega_2(\Psi_2 + \Gamma_2) + \Lambda_2\rho_{12}\right], \tag{14}$$

$$\Omega_3^{eff} = \left[\Omega_3(\Psi_3 + \Gamma_3) + \Lambda_3\rho_{13}\right], \tag{15}$$

$$\Omega_4^{eff} = \left[\Omega_4(\Psi_4 + \Gamma_4) + \Lambda_4\rho_{34}\right] \tag{16}$$

For the case (ZZY), we have:

$$\Omega_2 = \frac{\mu_{12}E_2}{\hbar\varepsilon_{effs}},\ \Omega_3 = \frac{\mu_{13}E_3}{\hbar\varepsilon_{effs}},\ \Omega_4 = \frac{\mu_{34}E_4}{\hbar\varepsilon_{effs}}, \tag{17}$$

$$\Psi_q = (1 + \sum_{j=1}^{3}\alpha_j A_j),\ \ (q = 2,3) \tag{18}$$

$$\Psi_4 = (1 + \sum_{j=1}^{3}\alpha_j C_j), \tag{19}$$

$$\Gamma_q = S_1\alpha_1\alpha_2(A_1 + A_2) + S_2\alpha_2\alpha_3(A_2 + A_3) + S_3\alpha_3\alpha_1(A_3 + A_1),\ \ (q = 2,3) \tag{20}$$

$$\Gamma_4 = T_1\alpha_1\alpha_2(C_1 + C_2) + T_2\alpha_2\alpha_3(C_2 + C_3) + T_3\alpha_3\alpha_1(C_3 + C_1) \tag{21}$$

$$\Lambda_q = \left(\frac{\mu_{1q}^2}{\hbar\varepsilon_{effs}}\right)\left[\sum_{j=1}^{3}\alpha_j A_j^2 + 2(S_1\alpha_1\alpha_2A_1A_2 + S_2\alpha_2\alpha_3A_2A_3 + S_3\alpha_3\alpha_1A_3A_1)\right],\ (q = 2,3) \tag{22}$$

$$\Lambda_4 = \left(\frac{\mu_{34}^2}{\hbar\varepsilon_{effs}}\right)\left[\sum_{j=1}^{3}\alpha_j B_j C_j + T_1\alpha_1\alpha_2(C_1B_2 + C_2B_1) + T_2\alpha_2\alpha_3(C_2B_3 + C_3B_2) + T_3\alpha_3\alpha_1(C_3B_1 + C_1B_3)\right] \tag{23}$$

where

$$\begin{aligned} A_j &= (3\cos^2\theta_j - 1)/4\pi\epsilon_o\epsilon_B r_j^3 \\ B_j &= (3\sin^2\theta_j - 1)/4\pi\epsilon_o\epsilon_B r_j^3 \\ C_j &= (3\sin\theta_j\cos\theta_j)/4\pi\epsilon_o\epsilon_B r_j^3 \end{aligned} \tag{24}$$

$$S_1 = \left\{3[(r_2\cos\theta_2 - r_1\cos\theta_1)/r_{21}]^2 - 1\right\}/4\pi\epsilon_o\epsilon_B r_{21}^3$$
$$S_2 = \left\{3[(r_3\cos\theta_3 - r_2\cos\theta_2)/r_{32}]^2 - 1\right\}/4\pi\epsilon_o\epsilon_B r_{32}^3$$
$$S_3 = \left\{3[(r_3\cos\theta_3 - r_1\cos\theta_1)/r_{31}]^2 - 1\right\}/4\pi\epsilon_o\epsilon_B r_{31}^3 \quad (25)$$

$$T_1 = 3[r_2\cos\theta_2 - r_1\cos\theta_1][r_2\sin\theta_2 - r_1\sin\theta_1]/4\pi\epsilon_o\epsilon_B r_{21}^5$$
$$T_2 = 3[r_3\cos\theta_3 - r_2\cos\theta_2][r_3\sin\theta_3 - r_2\sin\theta_2]/4\pi\epsilon_o\epsilon_B r_{32}^5$$
$$T_3 = 3[r_3\cos\theta_3 - r_1\cos\theta_1][r_3\sin\theta_3 - r_1\sin\theta_1]/4\pi\epsilon_o\epsilon_B r_{31}^5 \quad (26)$$

For the case (ZYZ), we have the same above equations $(14-26)$ but the subscript $(q=2,3)$ in Ψ_q, Γ_q and Λ_q can be exchange to the subscript $(q=2,4)$ and as well as the subscript 4 in Ψ_4, Γ_4 and Λ_4 exchange to the subscript 3 (i.e. the value of Ω_3^{eff} and Ω_4^{eff} exchange). For another special case (ZZY) under the condition $\alpha_1 = \alpha_2 = \alpha_3 = \alpha$ and $\theta_1 = 0$, $\theta_2 = \pi/2$, $\theta_3 = \pi$, we can get the property $\Omega_4^{eff} = \Omega_4$, this means that the main factor for obtain this result is the direction of the fields.

Under the electric-dipole approximation and the rotating-wave approximation, we define the equation of motion of density matrix elements (the master equation) of the SQD coupled to the three MNPs, as follows:

$$\dot{\rho_{22}} = i\ \Omega_2^{eff}\rho_{12} - i\ \Omega_2^{eff^*}\rho_{21} - 2\gamma_2\rho_{22} \quad (27)$$

$$\dot{\rho_{33}} = i\ \Omega_3^{eff}\rho_{13} - i\ \Omega_3^{eff^*}\rho_{31} - i\ \Omega_4^{eff}\rho_{34} + i\ \Omega_4^{eff^*}\rho_{43} - 2\gamma_3\ \rho_{33} + 2\gamma_4\ \rho_{44} \quad (28)$$

$$\dot{\rho_{44}} = i\ \Omega_4^{eff}\rho_{34} - i\ \Omega_4^{eff^*}\rho_{34} - 2\gamma_4\ \rho_{44} \quad (29)$$

$$\dot{\rho_{21}} = -\beta_2\rho_{21} - i\ \Omega_2^{eff}(\ \rho_{11} - \rho_{22}) - i\ \Omega_3^{eff}\rho_{23} \quad (30)$$

$$\dot{\rho_{31}} = -\beta_3\rho_{31} - i\ \Omega_2^{eff}\rho_{32} + i\ \Omega_3^{eff}(\ \rho_{11} - \rho_{33}) + i\ \Omega_4^{eff^*}\rho_{41} \quad (31)$$

$$\dot{\rho_{41}} = -\beta_4\rho_{41} - i\ \Omega_2^{eff}\rho_{42} - i\ \Omega_3^{eff}\rho_{43} + i\ \Omega_4^{eff}\rho_{31} \quad (32)$$

$$\dot{\rho_{32}} = -\beta_5\rho_{32} - i\ \Omega_2^{eff^*}\rho_{31} + i\ \Omega_3^{eff}\rho_{12} + i\ \Omega_4^{eff^*}\rho_{42} \quad (33)$$

$$\dot{\rho_{42}} = -\beta_6\rho_{42} - i\ \Omega_2^{eff^*}\rho_{41} + i\ \Omega_4^{eff}\rho_{32} \quad (34)$$

$$\dot{\rho_{43}} = -\beta_7\rho_{43} - i\ \Omega_3^{eff^*}\rho_{41} - i\ \Omega_4^{eff}(\ \rho_{44} - \rho_{33}) \quad (35)$$

with the identity $\sum_{n=1}^{4} \rho_{nn} = 1$ and

$$\beta_2 = \gamma_2 + i\Delta_2 \tag{36}$$
$$\beta_3 = \gamma_3 + i\Delta_3 \tag{37}$$
$$\beta_4 = \gamma_4 + i(\Delta_3 + \Delta_4) \tag{38}$$
$$\beta_5 = (\gamma_2 + \gamma_3) - i(\Delta_2 - \Delta_3) \tag{39}$$
$$\beta_6 = (\gamma_2 + \gamma_4) - i(\Delta_2 - \Delta_3 - \Delta_4) \tag{40}$$
$$\beta_7 = (\gamma_3 + \gamma_4) + i\Delta_4 \tag{41}$$

where γ_2, γ_3 and γ_4 represent the radiative decay rates of the excitation states $|2\rangle$, $|3\rangle$ and $|4\rangle$ due to spontaneous emission respectively. $\Delta_3 = \nu_3 - \omega_{31}$ is the frequency detuning for the weak probe field, $\Delta_2 = \nu_2 - \omega_{21}$ and $\Delta_4 = \nu_4 - \omega_{43}$ are the frequency detunings for the pump and control fields.

In the following section, we present the results of numerical calculations of the plasmonic effects and dipole–dipole interaction of the hybrid MNPs-SQD nano-system, where the SQD has a V-type four-level structure.

3 Numerical results and discussion:

The numerical calculations for the set of density- matrix eqns.$(27-35)$ at the steady-state are performed to obtain the coherence ρ_{13} and ρ_{34}. We study the influence of the strength of the plasmon-exciton dipole interaction as a function of probe field $\mathrm{Im}\,\Lambda_3\rho_{13} = \mathrm{Im}\,\eta_3$ and control field $\mathrm{Im}\,\Lambda_4\rho_{34} = \mathrm{Im}\,\eta_4$ for different parameters of the hybrid MNPs-SQD nano-system. We consider three spherical gold MNPs with radius a_j. The parameters of the MNPs-SQD are taken as $\hbar\omega_{pj} = 9.02\ eV$, $\gamma_{bj} = 0.026\ eV$, and the dipole $\mu_{12} = \mu_{13} = \mu_{34} = 0.65\ e\ nm, \gamma_2 = 0.02\ ns^{-1}$, $\gamma_3 = 1\ ns^{-1}, \gamma_4 = 0.01\ ns^{-1}, \Omega_3 = 0.01\ ns^{-1}, \Omega_2 = \Omega_4 = 6\ ns^{-1}$ and $(r_1, r_2, r_3) =$ 10, 26, 42 nm, respectively. We have $R_j = R = 7\ nm$, $\epsilon_s = 2$, $\epsilon_B = 12$, $\theta_2 = 2\pi/3$, $\theta_3 = 3\pi/2$, and $\Delta_2 = \Delta_4 = \Delta = 2\ eV$. Other parameters are indicated in the figure captions and described in what follows.

Fig.2 shows the spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_3$) of the hybrid MNPs-SQD nano-system for different values of $\theta_1(\pi/9, \pi/6, 5\pi/6)$ versus probe field detuning (Δ_3). Figs.2(a_1, a_2) are taken for case (ZZY) and Figs.2(b_1, b_2) are taken for case (ZYZ). While Figs.2(a_1, b_1) have the data: $\hbar\omega = 20\ eV$ and Figs.2(a_2, b_2) have the data: $\hbar\omega = 2.7\ eV$. Fig.2(a_1) shows different impacts and distinctive for the absorption spectra when $\hbar\omega = 20\ eV$ and have negative values for all θ_1, at small $\theta_1 = \pi/9$ (dashed curve), the absorption has an optical EIT window at zero detuning (Δ_3) beside one peak on each side. With increasing $\theta_1 = \pi/6$ (solid curve), we have three peaks and notice the optical EIT window disappearing, but at $\theta_1 = 5\pi/6$ (dashed-dotted curve), the peaks are increasing to four peaks. In Fig.2(a_2), the peaks are displacing under the effect of angle θ_1 where have four different peaks with positive values (because of the decreasing of $\hbar\omega = 2.7\ eV$). For case (ZYZ), we notice three peaks only, the peaks for large $\theta_1 = 5\pi/6$ have negative values in Figs.2(b_1). All the peaks for all values of θ_1, have negative values for ($\hbar\omega = 2.7$ eV) as in Figs.2(b_2) and also the peaks are displacing under the effect of angle θ_1 like Fig.2(a_2). We conclude in this figure, the absorption spectrum is asymmetric about the vertical axis at ($\Delta_3 = 0$), we notice also the resonance frequency ($\hbar\omega$) as well the angles and direction of the fields play an important role in the plasmon-exciton dipole coupling.

Fig.3 shows the spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_4$) of the hybrid MNPs-SQD nano-system for different values of $\theta_1(\pi/9,\, \pi/6,\, 5\pi/6)$ (as in Fig.2) versus probe field detuning (Δ_3). The data as in Fig. 2, in addition $\hbar\omega = 20\ eV$. We have Figs.3(a_1, a_2) for case (ZZY) and Figs.3(b_1, b_2) for case (ZYZ). While Figs.3(a_1, b_1) have the data: $\gamma_{bj} = 0.026\ eV$ and Figs.3(a_2, b_2) have the data: $\gamma_{bj} = 1.6\ eV$. At small damping constant ($\gamma_{bj} = 0.026\ eV$), For case (ZZY) as in Fig.3(a_1) we have an the optical EIT for small $\theta_1 = \pi/9$ (dashed curve). When increasing $\theta_1 = \pi/6$ (solid curve), the absorption have three peaks and the optical EIT disappear, but at $\theta_1 = 5\pi/6$ (dashed-dotted curve), It is observed four peaks with negative values. While For case (ZYZ) for all values of θ_1, we show three peaks only in the negative values with different heights as in Fig.3(b_1). Fig.3(a_2) display the effect of damping constant when it is large ($\gamma_{bj} = 1.6\ eV$) For case (ZZY), at $\theta_1 = \pi/9$, It is observed a hole in the left side which is converted into small peak at $\theta_1 = \pi/6$. But at $\theta_1 = 5\pi/6$, we find different two peaks with postive values in the left side and another different two peaks with negative values in the right side. We have in this figure zero absorption for all values of $\theta_1(\pi/9,\, \pi/6,\, 5\pi/6)$ at ($\Delta_3 = -3.2$) approximately. In Fig.3(b_2), we observe the middle peak have top value and another two peaks have small values for each value of $\theta_1$with different values for peaks. Then in Fig. 3, the influence of the damping constant on the plasmon-exciton dipole coupling are more obviously for the case (ZZY), also the shape of the spectra are asymmetric at ($\Delta_3 = 0$). As well, the optical PEIT in the spectrum is appearing at small damping constant and the hole in the spectrum is appearing at large damping constant .

Fig.4 shows the spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_4$) of the hybrid MNPs-SQD nano-system for different values of $\hbar\omega$ $(16, 6,\ 2.7)$ versus probe field detuning (Δ_3) at $\theta_1 = 0$. The another data as in Fig. 2. Figs.4(a_1, a_2, a_3) are taken for case (ZZY) and Figs.4(b_1, b_2, b_3) are taken for case (ZYZ). Figs.4(a_1, b_1) have the data: $\hbar\omega = 16\ eV$, Figs.4(a_2, b_2) have: $\hbar\omega = 6\ eV$ and Figs.4(a_3, b_3) have: $\hbar\omega = 2.7\ eV$. We have different impacts and distinctive for the resonance frequency ($\hbar\omega$) on the spectrum ($\mathrm{Im}\,\eta_4$) in this figure, when $\hbar\omega = 16\ eV$, Figs.4(a_1, b_1) display four peaks in the positive values for case (ZZY) and three peaks in the negative values for case (ZYZ) respectively with diffefent heights. But at $\hbar\omega = 6\ eV$ for case (ZZY), the spectrum exhibits a positive high peak with a Fano-like lineshape in the positive (Δ_3) and a negative small peak with a Fano-like lineshape in the negative (Δ_3) as in Fig.4(a_2). While in Fig.4(b_2), the spectrum exhibits a negative high peak in the negative (Δ_3) and small peak with a Fano-like lineshape in the positive (Δ_3). At $\hbar\omega = 2.7\ eV$ for case (ZZY), Fig.4(a_3) displays a positive and a negative peaks in the negative (Δ_3) and also in the positive (Δ_3). For case (ZYZ) in Fig.4(b_3) the spectrum exhibits a trapping at ($\Delta_3 = 0$), we notice also a negative peak at a certain values ($\Delta_3 = -30$) and also a positive peak at ($\Delta_3 = 30$) approximately. We conclude in this figure, the obviously role of the resonance frequency ($\hbar\omega$) or the dielectric function $\epsilon_{m_j}(\omega)$ for MNPs on the spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_4$). So it is clearly the influence of the metal nanoparticles is to enhance different phenomena in the regime of exciton–plasmon resonance.

Fig.5 demonstrates the spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_3$) and ($\mathrm{Im}\,\eta_4$) of the hybrid MNPs-SQD nano-system for case (ZZY) when the dielectric constant ϵ_B is small and equal ϵ_s ($\epsilon_B = \epsilon_s = 2$) at $\hbar\omega = 20$ eV. The dashed curve for $\Omega_2 = \Omega_4 = 6ns^{-1}$ and the solid curve for $\Omega_2 = 4ns^{-1}, \Omega_4 = 8ns^{-1}$. The another data as in Fig.4. Figs.5(a_1, a_2, a_3) are taken for ($\mathrm{Im}\,\eta_3$), where the spectra have negative values and Figs.5(b_1, b_2, b_3) are taken for (($\mathrm{Im}\,\eta_4$), where the spectra have positive values. Figs.5(a_1, b_1) have ($\Delta = 0$), Figs.5(a_2, b_2) have ($\Delta = 2$) and Figs.5(a_3, b_3) have ($\Delta = 5$). The optical EIT, when ($\Omega_2 = \Omega_4 = 6ns^{-1}$) (in Figs.5($a_1, b_1$)), is deep and disappear when increasing the (Δ) (as in Figs.5(a_3, b_3)) . As well a four peaks are appeared for ($\Omega_2 = 4ns, \Omega_4 = 8ns^{-1}$) in Figs.5($a_1, b_1$) and decreased to only two peaks when increasing the (Δ) (in Figs.5(a_3, b_3)). Then the optical EIT are related by the change of (Δ) and the value of the (Δ) plays an important role in the characterization of the spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_3$) and ($\mathrm{Im}\,\eta_4$).

Fig.6 exhibits the spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_3$) and ($\mathrm{Im}\,\eta_4$) of the hybrid MNPs-SQD nano-system when the dielectric constant ϵ_s is large ($\epsilon_s = 12$), unlike the above figures, at ($\Delta = 0$ and $\theta_1 = \pi/9$). Figs.6(a_1, a_2) are taken for ($\mathrm{Im}\,\eta_3$) and Figs.6(b_1, b_2) are taken for (($\mathrm{Im}\,\eta_4$). Figs.6(a_1, b_1) for case (ZZY) and Figs.6(a_2, b_2) for case (ZYZ). The (dashed-dotted curve) for ($\epsilon_B = 2$), the solid curve for ($\epsilon_B = 6$) and the (dashed curve) for ($\epsilon_B = 12$). The another data as in Fig. 2. We see that, when the dielectric constant ϵ_s is large, the increasing of the dielectric constant ϵ_B can be contributed to the enhancement of the optical EIT for case (ZZY) in the spectrums of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_3$ and $\mathrm{Im}\,\eta_4$), when $\epsilon_s = \epsilon_B = 12$, the optical EIT becomes more deep. The optical EIT for case (ZYZ) in the spectrums ($\mathrm{Im}\,\eta_3$ and $\mathrm{Im}\,\eta_4$) are not available, the three peaks more extend range at increasing the dielectric constant ϵ_B in Figs.6(a_2, b_2). So, the happening of the optical EIT is related by the value of the dielectric constants ϵ_B, ϵ_s and the direction of the fields.

Fig.7 demonstrates the influence of the size of the three sphericals MNPs on the spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_3$) and ($\mathrm{Im}\,\eta_4$) of the hybrid MNPs-SQD nano-system for case (ZZY), we take the radii with two different values ($R = 4, 6$ nm) and ($\theta_1 = 0$). Figs.7(a_1, a_2) are taken for ($\mathrm{Im}\,\eta_3$) and Figs.7(b_1, b_2) are taken for (($\mathrm{Im}\,\eta_4$). Figs.7(a_1, b_1) are plotted versus probe field detuning (Δ_3) and Figs.7(a_2, b_2) are plotted versus probe field detuning (Δ_4). The dashed curve for ($R = 4$), the solid curve for ($R = 6$). The another data as in Fig.2. We notice at ($R = 4$), the spectrum have small optical EIT, when increasing the radii ($R = 6$) the optical EIT becomes broad as in Figs.7(a_1, b_1, a_2, b_2). In Figs.7(a_2, b_2), where the plotted versus probe field detuning (Δ_4), it is not shown peaks on the two sides of the spectrum as in Figs.7(a_1, b_1). Then the spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_3$) and ($\mathrm{Im}\,\eta_4$) of the hybrid MNPs-SQD nano-system are affected by the size of the three sphericals MNPs and the detunings (Δ_3, Δ_4).

4 Conclusion:

We have derived a compound expression of the effective Rabi frequencies based on the effect of the plasmon-exciton dipole coupling in the SQD-MNPs nanosystem which is composed of three sphere metallic nanoparticles (MNPs) and semiconductor quantum dot (SQD) which having three external fields. The strong exciton-plasmon interaction and multipole effects are considered the main focus of this work.The direction and detunings of the three external fields are played an important role on the characterization of the SQD-MNPs nanosystem. We investigated the dependence of the plasmon-exciton dipole coupling of the SQD-MNP nanosystem on the distance between the three MNPs and also the distance between SQD and MNPs. The material parameters of the hybrid nanosystem, (such as resonance frequency, damping constant, dielectric constant), are demonstrated for many distinct characteristics and phenomena for the spectra of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\Lambda_3\rho_{13}$) and ($\mathrm{Im}\,\Lambda_4\rho_{34}$) of the hybrid MNPs-SQD nano-system. The optical experiments on the hybrid SQD-MNPs nanosystem may be analyzed by using the results obtained in this work.

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6 References:

[1] E. Paspalakis, S. Evangelou, V. Yannopapas, A. F. Terzis, Phase-dependent optical effects in a four-level quantum system near a plasmonic nanostructure, Phys. Rev. A 88 (2013) 053832.
[2] S. G. Kosionis, A. F. Terzis, S. M. Sadeghi, E. Paspalakis, Optical response of a quantum dot–metal nanoparticle hybrid interacting with a weak probe field, J. Phys. Condens. Matter 25 (2013) 045304.
[3] Yanlian Yang, Kangxian Guo, Tao Yang, Keyin Li, Wangjian Zhai, Enhancement of linear and nonlinear optical absorption coefficients in spherical dome semiconductor nanoshells by surface plasmon resonances, Physica B: Condensed Matter 556 (2019) 158–162.
[4] R. D. Artuso, G. W. Bryant, Strongly coupled quantum dot-metal nanoparticle systems: Exciton-induced transparency, discontinuous response, and suppression as driven quantum oscillator effects, Phys. Rev. B 82 (2010) 195419.
[5] Zhang W, Govorov A O, Quantum theory of the nonlinear Fano effect in hybrid metal-semiconductor nanostructures: The case of strong nonlinearity, Phys. Rev. B 84 (2011) 081405 (R).
[6] Jian Cui, Boyu Ji, Xiaowei Song, Jingquan Lin, Efficient Modulation of Multipolar Fano Resonances in Asymmetric Ring-Disk/Split-Ring-Disk Nanostructure, Plasmonics (2018)
[7] Dongxing Zhao, Jiarui Wu, Ying Gu, Qihuang Gong, Tailoring double Fano profiles with plasmon-assisted quantum interference in hybrid exciton-plasmon system, Applied Physics Letters 105, (2014)111112.
[8] Wei Zhang, Alexander O. Govorov, Garnett W. Bryant, Semiconductor-Metal Nanoparticle Molecules: Hybrid Excitons and the Nonlinear Fano Effect, Physical Review Letters 97(2006) 146804.
[9] Hatef A, Sadeghi S M, Singh M R, Plasmonic electromagnetically induced transparency in metallic nanoparticle–quantum dot hybrid systems, Nanotechnology 23 (2012) 065701.
[10] Naser Zamani, Ali Hatef, Hamid Nadgaran, Alireza Keshavarz, “Control of electromagnetically induced transparency via a hybrid semiconductor quantum dot–vanadium dioxide nanoparticle system,” J. Nanophotonics 11(3), (2017) 036011.
[11] Behjat Behroozian, Mohammad Reza Rezaie, Hassan Ranjbar Askari,

The dispersion behaviors of the tripod-type four-level cylindrical quantum dot under phenomenon of electromagnetically induced transparency, Phys. Scr. 95 (2020) 065506.
[12] S M Sadeghi, L Deng, X Li, W-P Huang, Plasmonic (thermal) electromagnetically induced transparency in metallic nanoparticle–quantum dot hybrid systems, Nanotechnology, 20, (2009) 365401.
[13] S. Evangelou, V. Yannopapas, E. Paspalakis, Modification of Kerr nonlinearity in a four-level quantum system near a plasmonic nanostructure, Journal of Modern Optics, Vol. 61, No. 18, (2014) 1458–1464.
[14] A.F.Terzis, S.G. Kosionis, J. Boviatsis, E. Paspalakis, Nonlinear optical susceptibilities of semiconductor quantum dot – metal nanoparticle hybrids, Journal of Modern Optics, Vol. 63, No. 5, (2016) 451–461.
[15] Zhien Lu, Ka-Di Zhu, Enhancing Kerr nonlinearity of a strongly coupled exciton–plasmon in hybrid nanocrystal molecules, J. Phys. B: At. Mol. Opt. Phys. 41 (2008) 185503.
[16] Spyridon G. Kosionis, Andreas F. Terzis, Constantinos Simserides, E. Paspalakis, Linear and nonlinear optical properties of a two-subband system in a symmetric semiconductor quantum well, Journal of Applied Physics, 108, (2010) 034316.
[17] F.Carreno, M. A. Anton, Sonia Melle, Oscar G. Calderon, E.Cabrera-Granado, Joel Cox, Mahi R. Singh, A. Egatz-G omez, Plasmon-enhanced terahertz emission in self-assembled quantum dots by femtosecond pulses, Journal of Applied Physics,115, (2014) 064304.
[18] S. M. Sadeghi, A Hatef, Simon Fortin-Deschenes, Michel Meunier, Coherent confinement of plasmonic field in quantum dot–metallic nanoparticle molecules, Nanotechnology 24 (2013) 205201.
[19] Ryan D. Artuso, Garnett W. Bryant, Using local fields to tailor hybrid quantum-dot/metal nanoparticle systems, Physical Review B 83, (2011) 235406,.
[20] S M. Sadeghi, Gain without inversion in hybrid quantum dot–metallic nanoparticle systems, Nanotechnology 21 (2010) 455401.
[21] S. M. Sadeghi, Dynamics of plasmonic field polarization induced by quantum coherence in quantum dot–metallic nanoshell structures, Optics Letters, Vol. 39, (2014).
[22] S. M. Sadeghi, Chuanbin Mao, Quantum sensing using coherent control of near-field polarization of quantum dot-metallic nanoparticle molecules, Journal of Applied Physics,121 (2017) 014309 .
[23] Bintoro S. Nugroho, Alexander A. Iskandar, Victor A. Malyshev, Jasper Knoester, Plasmon-assisted two-photon Rabi oscillations in a semiconductor quantum dot – metal nanoparticle heterodimer, Physical Review B 99, (2019) 075302 .
[24] Jie-Yun Yan, Wei Zhang, Suqing Duan, Xian-Geng Zhao, Alexander O. Govorov, Optical properties of coupled metal-semiconductor and metal-molecule nanocrystal complexes: Role of multipole effects,

Physical Review B 77 (2008) 165301.
[25] M. A. Anton, F. Carreno, Sonia Melle, Oscar G. Calderon, E. Cabrera-Granado, Optical pumping of a single hole spin in a p-doped quantum dot coupled to a metallic nanoparticle, Physical Review B 87 (2013) 195303.
[26] Joel D. Cox, Mahi R. Singh, Godfrey Gumbs, Miguel A. Anton, Fernando Carreno, Dipole-dipole interaction between a quantum dot and a graphene nanodisk, Physical Review B 86 (2012) 125452.
[27] Xiancong Jiang, Kangxian Guo, Guanghui Liu, Tao Yang, Yanlian Yang, Enhancement of surface plasmon resonances on the nonlinear optical properties in a GaAs quantum dot, Superlattices and Microstructures 105 (2017) 56-64.
[28] Stefan A. Maier, Plasmonics: Fundamentals and Applications, 2007 Springer Science.

7 Figures Captions:

Fig.1: A schematic diagram of the SQD and three MNPs (hybrid system). SQD have four-level V-type configuration coupling with three fields.

Fig.2: The spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_3$) of the hybrid MNPs-SQD nano-system versus probe field detuning (Δ_3). $\epsilon_s = 2, \epsilon_B = 12, \theta_2 = 2\pi/3$, $\theta_3 = 3\pi/2$, $\Omega_2 = \Omega_4 = 6\ ns^{-1}$and $\Delta_2 = \Delta_4 = \Delta = 2\ eV$. Figs.2$(a_1, a_2)$ for (ZZY) and Figs.2(b_1, b_2) for (ZYZ). Figs.2(a_1, b_1) have: $\hbar\omega = 20\ eV$ and Figs.2(a_2, b_2) have: $\hbar\omega = 2.7\ eV$. $\theta_1 = \pi/9$ (dashed curve), $\theta_1 = \pi/6$ (solid curve) and $\theta_1 = 5\pi/6$ (dashed-dotted curve).

Fig.3: The spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_4$) of the hybrid MNPs-SQD nano-system versus probe field detuning (Δ_3). The data as in Fig. 2, in addition $\hbar\omega = 20\ eV$. Figs.3(a_1, a_2) for (ZZY) and Figs.3(b_1, b_2) for (ZYZ). Figs.3(a_1, b_1) have: $\gamma_{bj} = 0.026\ eV$ and Figs.3(a_2, b_2) have: $\gamma_{bj} = 1.6\ eV$.

Fig.4: The spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_4$) of the hybrid MNPs-SQD nano-system versus probe field detuning (Δ_3) at $\theta_1 = 0$. Figs.4(a_1, a_2, a_3) for (ZZY) and Figs.4(b_1, b_2, b_3) for (ZYZ). Figs.4(a_1, b_1): $\hbar\omega = 16\ eV$, Figs.4(a_2, b_2) have: $\hbar\omega = 6\ eV$ and Figs.4(a_3, b_3) have: $\hbar\omega = 2.7\ eV$. The another data as in Fig. 2.

Fig. 5: The spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\,\eta_3$) and ($\mathrm{Im}\,\eta_4$) of the hybrid MNPs-SQD nano-system for (ZZY) at ($\epsilon_B = \epsilon_s = 2$), $\hbar\omega = 20\ eV$. Figs.5(a_1, a_2, a_3) are for ($\mathrm{Im}\,\eta_3$)and Figs.5(b_1, b_2, b_3) for (($\mathrm{Im}\,\eta_4$). Figs.5(a_1, b_1) have ($\Delta = 0$), Figs.5(a_2, b_2) have ($\Delta = 2$) and Figs.5(a_3, b_3) have ($\Delta = 5$).

The dashed curve for $\Omega_2 = \Omega_4 = 6ns^{-1}$ and the solid curve for $\Omega_2 = 4ns^{-1}, \Omega_4 = 8ns^{-1}$. The another data as in Fig. 4.

Fig. 6: The spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\, \eta_3$) and ($\mathrm{Im}\, \eta_4$) of the hybrid MNPs-SQD nano-system at $\epsilon_s = 12$, $\Delta = 0$ and $\theta_1 = \pi/9$. Figs.6(a_1, a_2) for ($\mathrm{Im}\, \eta_3$) and Figs.6(b_1, b_2) for (($\mathrm{Im}\, \eta_4$). Figs.6(a_1, b_1) for (ZZY) and Figs.6(a_2, b_2) for (ZYZ).The (dashed-dotted curve) for ($\epsilon_B = 2$), the solid curve for ($\epsilon_B = 6$) and the (dashed curve) for ($\epsilon_B = 12$) .The another data as in Fig. 2.

Fig. 7: The spectrum of the plasmon-exciton dipole interaction ($\mathrm{Im}\, \eta_3$) and ($\mathrm{Im}\, \eta_4$) of the hybrid MNPs-SQD nano-system for (ZZY), at ($R_j = 4, 6\ nm$) and ($\theta_1 = 0$). Figs.7(a_1, a_2) for ($\mathrm{Im}\, \eta_3$) and Figs.7(b_1, b_2) for (($\mathrm{Im}\, \eta_4$). Figs.7(a_1, b_1) are plotted versus probe field detuning (Δ_3) and Figs.7(a_2, b_2) are plotted versus probe field detuning (Δ_4). The dashed curve for ($R_j = 4$), the solid curve for ($R_j = 6$). The another data as in Fig.2.

Figures

Figure 1

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Figure 2

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Figure 3

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Figure 4

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Figure 5

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Figure 6

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