Modification of a plasmonic nanoparticle lifetime by coupled quantum dots

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In this study, the interaction between a plasmonic nanoparticle and coupled quantum dots is investigated to identify how the coupled particles can manipulate the plasmonic nanoparticle decay rate. This subject is very important, because most applications of the plasmonic system are restricted due to the nanoparticle decay rate and the related losses. Therefore, in the present work, we try to find out how and by which method the plasmonic nanoparticle decay rate can be manipulated. For this purpose, a plasmonic system containing a nanoparticle coupled to some small quantum dots is designed. The system dynamics of motions are analyzed with Heisenberg-Langevin equations. These equations are analyzed to study the effect of the plasmonic nanoparticles on the quantum dots' decay rate. In the following, as an interesting point, the quantum dot coupling influence on the nanoparticle's decay rate is theoretically analyzed in the transient and steady-state conditions. Additionally, a theoretical formula is derived by which one can explicitly find the dependency of the modified decay rate of the plasmonic nanoparticle on the number of the coupled quantum dots and the coupling strength. The simulation results show that it is possible to effectively control the nanoparticles' decay rate with regard to the application for which they are utilized.

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I. INTRODUCTION

Recently, the plasmonic effect has been widely utilized in different applications such as highly sensitive sensors [1,2], quantum imaging [3], imaging filters [4,5], imaging resolution enhancing [6], sensitive plasmonic-photonic nanosensors [7], and Raman signal enhancing [8]. In general, plasmonic property refers to harmonious oscillating of the surface charges of noble metal interacting with the incident wave [9–11]. By interaction of an incident wave with a metal, an intense field is generated close to the surface where the interaction took place. This field is known as the plasmonic field and, in most applications, is utilized as same role as the radio-frequency antenna to amplify the incident wave [12,13]. It has been reported that the plasmonic field is efficiently coupled to any small particles such as quantum dots (QDs) embedded at the region's so-called hot spot [9,10]. The coupling of the plasmonic nanoparticle (NP) to QDs has been applied because of the above-mentioned advantages, which suggest that the optical properties of the system (NP-QDs) are changed by considering the coupling effects. This alteration due to the coupling effect is a critical case in numerous applications such as in sensory applications [4–8]. Due to the important role of the plasmonic field, several studies have been conducted on plasmonic field engineering using nanotechnology to convert the plasmonic field to the lattice plasmonic field [5,14]. In this case, the plasmonic field operates as a laser with a high-intensity field and very narrow bandwidth.

However, in this article, we focus on the interaction of the plasmonic NP with QDs, and it is shown how the coupled system's optical properties can be manipulated. Accordingly, it is found that some intrinsic properties of the coupled particles such as NP's decay rates are altered. The NP's plasmonic field effect on the QDs' decay rate (i.e., the Purcell factor) has been studied in recently published works [9,10]. It has been proved that the NP-QDs' interdistance changing manipulates the coupling strength between the NP and the QDs, then, leading to dramatic changing in the QDs' decay rates. Additionally, in some interesting works, the NPs coupling to the QDs' spacer has been theoretically and experimentally investigated [15–17]. In [15], the authors proposed a way to excite the local field using plasmon resonance through spacer radiation. This radiation has a unique ability, in contrast to photons, such that it can be localized on the nanoscale. Therefore, it can be imagined as the plasmon resonance squeezed state. The latter important property has been deeply investigated [18], indicating that the plasmonic mode can be squeezed into a volume far below the diffraction limit. Another interesting work studied the spacer as a nanoscale quantum amplifier in which the spacer can be function as an ultrafast nanoamplifier [16]. The main problem of the spacer, which is the inherent feedback, is the quantum generation of localized surface plasmon and eliminating the net gain. This issue has contributed to the plasmonic field effect on the QDs' transition rates.

However, all the similar studies in the case of the spacer have investigated either the effect of the NPs' plasmonic field on the QDs' optical properties or the QDs' effect on the localized field close to the NPs. Meanwhile, it seems that it should be necessary to study the effect of the QDs' coupling strength on the NP decay rate. The most interesting point of this study is that the decrease of the NP's decay rate strongly enhances the plasmonic applications; for instance, plasmon resonance mode entanglement [4,18,19] can be largely improved due to the plasmonic mode lifetime increasing. Therefore, in this article, it is theoretically shown that the QDs attached can dramatically modify the NP's decay rate. Notably, we just focus on the hot-spot region where the QDs are embedded. This region is the area where the plasmonic field is maximized

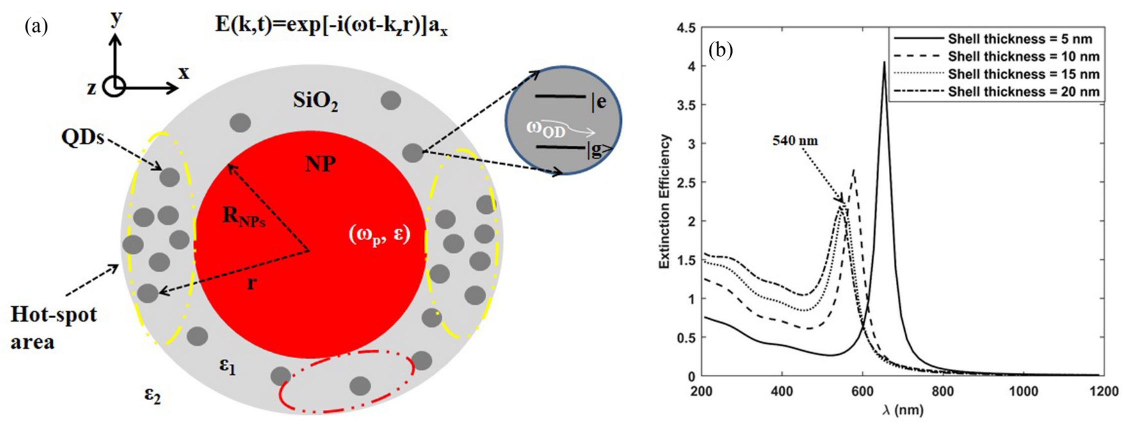

FIG. 1. (a) Illustration of the system schematic, plasmonic NP surrounded by the embedded QDs; r shows the position of the QDs, (ω_p, ε) indicate the plasmonic NP optical properties, $\varepsilon_1 = 2.1$ and ε_2 stand for SiO_2 and host medium dielectric constants, ω_{QD} indicates QDs resonance frequency, and incoming wave is incident with frequency ω in the z direction with x coordinate polarization. (b) The effect of the SiO_2 shell thickness on the extinction efficiency of the core-shell NP vs incident wavelength (nm).

and then the maximum amount of the energy is transferred to the coupled particles [20,21]. In the following, the theory and background of the system are introduced and then the results of the simulations are presented.

II. THEORY AND BACKGROUND

A. System description and the Hamiltonian

The designed system is schematically illustrated in Fig. 1(a). It shows a core-shell NP with some coupled QDs at the shell region. In this design, we considered the Au NP with a radius around 25 nm. Also, it is assumed that the QDs' radius is 2–3 nm and all of the QDs are randomly embedded into the dielectric shell like SiO_2 with a thickness between 12 and 20 nm. In fact, it is selected based on the effect of the SiO_2 shell thickness on the plasmon resonance of the core-shell NPs. For better understanding, the effect of the SiO_2 shell thickness is investigated on the core-shell NP's extinction efficiency [Fig. 1(b)]. It is shown that by increasing the shell thickness, the contributed profile has a blueshift, and also the related amplitude is decreased. For example, when the shell thickness is 15 nm, the plasmon resonance wavelength is around 540 nm. This means that the incident wave frequency should be tuned around a frequency that has a maximum overlap with the extinction efficiency profile to transfer the energy efficiently to the system. Additionally, it is supposed that the incoming wave is excited in the z direction. It should be noted that we just trace the QDs that are embedded in the hot-spot area of the NP; this means that the NP-QDs' coupling strength is much stronger than the QD-QD interaction strength. Moreover, it is supposed that the considered QDs have a two-level energy.

The NP's plasmonic field is semiclassically defined in the radial direction as $E_{\text{NPs}}(r,\theta) = E_0\{0.5\omega_0/(\omega - \omega_0 - i0.5\kappa_0)\}[(-R_{\text{NPs}}/r)^3 2\cos(\theta)]$ [10] where E_0, κ_0, ω, R_{NPs}, and r are the incidence electric field amplitude, plasmon frequency, the NP decay rate, incident frequency, the NP radius, and QDs' position, respectively. Also, $\omega_0 = \omega_p/\sqrt{(2\varepsilon_1 + 1)}$ where ω_p and ε_1 are the NP's plasmon frequency and the host medium dielectric constant (SiO_2), respectively. From $E_{\text{NPs}}(r,\theta)$, it is understandable that at $\theta = 0^\circ$, the maximum amplification occurs which is marked with the yellow-dashed circle in Fig. 1(a). Also, it is easy to show that either by increasing the QDs' distance from the NP (r) or when $\theta > 80^\circ$, the field intensity dramatically declines [20,21]; this is indicated by the red-dashed circle on the figure. Therefore, at the hot-spot region a more intense localized plasmon field can be found which is the main factor for effective coupling between the NP and the embedded QDs. After a short description about the system and the related plasmonic field distribution, we start with the system dynamics of motion (one NP coupling to one QD) derived by the master equation [10]. Then, we can expand the theory for N coupled QDs to one NP. Accordingly, the present system's Hamiltonians are introduced as

$$\begin{aligned} H_0 &= E_g\sigma_{gg} + E_e\sigma_{ee} + \hbar\omega_p a^\dagger a, \\ H_{I,\text{eff}} &= \hbar g(r)(a^\dagger\sigma_- + a\sigma_+), \quad \sigma_- = \sigma_{eg}, \\ H_{\text{drive}} &= i\hbar\sqrt{\kappa_0}[a^\dagger\varepsilon e^{-i\omega t} - a\varepsilon^* e^{i\omega t}] \\ &\quad + i\hbar[\sigma_+\Omega e^{-i\omega t} - \sigma_-\Omega^* e^{i\omega t}], \end{aligned} \tag{1}$$

where H_0, $H_{I,\text{eff}}$, and H_{drive} are the unperturbed Hamiltonian, interaction Hamiltonian between plasmonic NP and QD, and the driving Hamiltonian which is the direct interaction of the incoming wave with NP-QD, respectively. Notably, we consider the direct interaction of the incoming light with QDs as the driving Hamiltonian (through factor Ω). It means that only the QD-QD interaction Hamiltonian ($H_{\text{QD}-\text{QD}}$) is ignored. It is because, for simplicity, we just study the interaction between the NP and QDs at the hot-spot region where the plasmonic field interaction with the QDs is much stronger than the QD-QD interaction strength. Another reason is that one can easily linearize the dynamics equations of the system around the fix point at which the maximum amount of the plasmonic field is produced [19,22] and coupled between NP and QDs. In other words, the many-body effects due to coupling between the quantum dots can be ignored at the hot-spot region. Accordingly, the latter assumption is valid just for the hot-spot region, not for everywhere around the NPs.

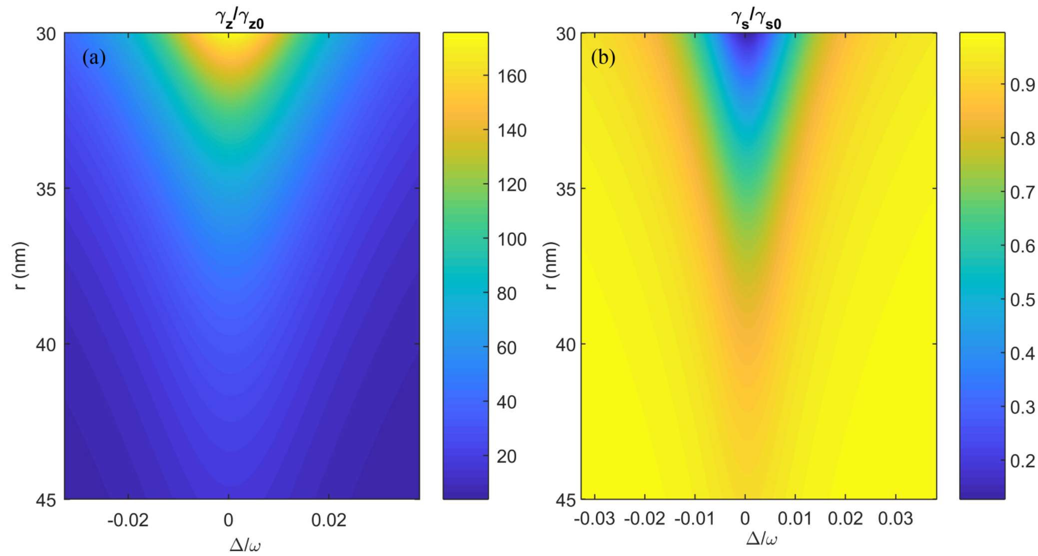

FIG. 2. NP's plasmonic field effect on the QDs' decay rates; (a) spontaneous emission vs QDs' position around the NP and detuning frequency, (b) dephasing rate vs QDs' position around the NP and detuning frequency.

In Eq. (1), σ_{ii}, E_i, ω_p, ε, Ω, and a, $a^\dagger$ are the atomic transition operator, level energy, plasmon frequency, NP's and QDs' driving field [10,11], and the plasmonic field operators, respectively. It should be noted that the NP's Ohmic loss and the loss due to the scattering into free space are issued because of the NP's decay rate [10]. Also, the NP-QD coupling strength $g(r) = (-2\mu/\hbar)(R_{\text{NPs}}/r)^3\sqrt{(\hbar\omega_0/(2\varepsilon_0 V_m))}$ [9,10], where μ, V_m, ε_0, and $\hbar$ are the dipole momentum of the transition, the considered volume, free space dielectric constant, and Planck's constant, respectively. Finally, $\Omega = iE_0\mu/2\hbar$ [10] is the classical Rabi frequency for the external field direct-driving the QD. Other Hamiltonians which should be considered are the reservoir mode Hamiltonian and the system-reservoir modes interaction Hamiltonian [9,10]. These Hamiltonians basically interpret the interaction of the system with environment and noise effect. The effect of the Hamiltonians mentioned above will be considered when we derive the master equation for the deigned system.

B. System dynamics of motions using Heisenberg-Langevin equations

The system equations of motions using master equations $dA/dt = [A, H_t]/i\hbar - \kappa_0\{2aAa^\dagger - a^\dagger aA - Aa^\dagger a\} + \gamma_{z0}\{2\sigma_- A\sigma_+ - \sigma_+\sigma_- A - A\sigma_+\sigma_-\}/2 + \gamma_{s0}\{2\sigma_+\sigma_- A\sigma_+\sigma_- - \sigma_+\sigma_- A - A\sigma_+\sigma_-\}$ [10] are presented as

$$\begin{aligned}
\dot{a} &= -(i\omega_p + \kappa_0/2)a - ig(r)\sigma_- + \sqrt{\kappa_0}\varepsilon e^{-i\omega t},\\
\dot{\sigma}_- &= -(i\omega_{\text{QD}} + \gamma_{s0})\sigma_- + ig(r)a\sigma_z - \Omega\sigma_z,\\
\dot{\sigma}_z &= -\gamma_{z0}(\sigma_z - \sigma_0) + i2g(r)[a^+\sigma_- - \sigma_+ a] + 2\Omega[\sigma_- + \sigma_+],
\end{aligned} \tag{2}$$

where γ_{z0}, γ_{s0}, σ_-, σ_+, $\sigma_z = \sigma_{ee} - \sigma_{gg}$, and ω_{QD} are the QDs' unmodified spontaneous emission rate, dephasing transition rate, QD's lowering operator, QD's raising operator, population difference, and QD dipole resonance frequency, respectively.

By neglecting the fast oscillating terms which are performed using the rotating frame approximation [10] in Eq. (2) at $\pm\omega$, with substituting $a = ae^{-i\omega t}$ and $\sigma_- = \sigma_- e^{-i\omega t}$, the system dynamics of motions is rewritten as

$$\begin{aligned}
\dot{a} &= -(i\Delta + \kappa_0/2)a - ig(r)\sigma_- + \sqrt{\kappa_0}\varepsilon,\\
\dot{\sigma}_- &= -(i\Delta_e + \gamma_{s0})\sigma_- + ig(r)a\sigma_z - \Omega\sigma_z,\\
\dot{\sigma}_z &= -\gamma_{z0}(\sigma_z - \sigma_0) + i2g(r)[a^\dagger\sigma_- - \sigma_+ a] + 2\Omega[\sigma_- + \sigma_+],
\end{aligned} \tag{3}$$

where $\Delta = \omega_p - \omega$ and $\Delta_e = \omega - \omega_{\text{QD}}$ are the incident wave detuning parameters for the plasmon field and the QDs' transition frequency, respectively. With regard to Eq. (3), one can theoretically derive the effect of the NP's plasmonic field on the QDs' transition rate and dephasing rate in the steady-state condition. For evaluating, it should substitute the steady-state solution of the plasmonic mode which is $a = [\varepsilon\sqrt{\kappa_0} - ig(r)\sigma_-]/(i\Delta + 0.5\kappa_0)$ into $d\sigma_z/dt$ and $d\sigma_-/dt$ of Eq. (3), which leads to

$$\begin{aligned}
\dot{\sigma}_- &= -(i\Delta_e + \gamma_s)\sigma_- - \Omega_t\sigma_z,\\
\dot{\sigma}_z &= -\gamma_z(\sigma_z - \sigma_0) + 2(\Omega_t{}^*\sigma_- + \Omega_t\sigma_+),
\end{aligned} \tag{4}$$

where $\gamma_z = \gamma_{z0} + [4g(r)^2\kappa_0]/(\Delta^2 + \kappa_0{}^2)$ and $\gamma_s = \gamma_{s0} + [\sigma_z g(r)^2]/(i\Delta + 0.5\kappa_0)$ are the modified spontaneous and dephasing rates, respectively. Also, in this equation, the modified QD's driving field is defined as $\Omega_t = \Omega - [ig(r)\varepsilon\sqrt{\kappa_0}]/(i\Delta + 0.5\kappa_0)$. Consequently, these are the rates (γ_z and γ_s) by which the system's quantum mechanical states alter from one state and transfer to another either as a pure state or with different phases. Herein, it is theoretically shown that the QD's transition and dephasing rates are strongly affected by the NP-QD coupling strength, so that, the QD's basic parameters are easily influenced by the plasmon field effect. To study the effect of the NP plasmonic field on the QD's decay rates such as spontaneous emission and dephasing rate, some simulations are carried out (Fig. 2).

From Fig. 2, it is observable that the spontaneous emission rate is more efficiently affected rather than the dephasing rate, which is understood through the γ_z and γ_s formulas. Moreover, it is shown that in the vicinity of the NP, the QD's decay rates are dramatically changed. Such a change is contributed to the NP-QD coupling strength, which indicates that by increasing the NP and QD interdistance, the strength factor is declined. The results illustrated in Fig. 2 are comparable with the results in published articles [9,10]. Additionally, from Eq. (4), it is understandable that the amplitude of the modified decay rates is strongly increased with a decrease in detuning frequency ($\Delta \sim 0$).

The interesting point that we analyzed in this study is the QD's coupling effect on the NP's decay rate. For this purpose, using Eq. (3), we substitute the steady-state solution of $\sigma_- = [ig(r)a\sigma_z - \Omega\sigma_z]/(i\Delta_e + \gamma_{s0})$ in da/dt, which leads to $\kappa_m = 0.5\kappa_0 - \sigma_z g(r)^2/(i\Delta_e + \gamma_{s0})$. This is the modified plasmonic NP decay rate, which is strongly affected by the NP-QD coupling strength. More importantly, the sign of QD's population difference (σ_z) is a critical factor.

Therefore, in this study, we attain a degree of freedom to manipulate the plasmonic system properties. For instance, by decreasing the NP's decay rate, the induced dispersion rate due to the plasmonic system is dramatically decreased. This point is very important for the case of the plasmonic sensor designing. However, for a complete investigation of the QDs' effect on the NP modified decay rate, one has to know about the QDs' population difference behavior. In the steady-state condition, it can be derived from Eq. (3) as

$$\sigma_z = \frac{\gamma_z\sigma_0}{\gamma_{z0} + \frac{4g(r)^2 a^\dagger a \gamma_{s0}}{\gamma_{s0}{}^2 + \Delta_e{}^2}} \xrightarrow{N_p = a^\dagger a} = \frac{\gamma_z\sigma_0}{\gamma_{z0} + \frac{4g(r)^2 N_p \gamma_{s0}}{\gamma_{s0}{}^2 + \Delta_e{}^2}}, \quad (5)$$

where N_p is the plasmonic field photons' number and σ_0 is the QDs' initial population difference in the equilibrium condition. It should be noted that in Eq. (5), for the sake of simplicity and clarity, the effect of the QDs' driving field is ignored.

In the following, the effect of the QDs on the NP decay rates is simulated (Fig. 3). In this simulation, it is supposed that $\sigma_0 = -1$; however, it seems to be a logical assumption in a two-level system. In Fig. 3(a), the alteration of the population difference σ_z as a function of the QDs' location and the detuning frequency Δ is considered. From Eq. (5), it is clearly perceptible that σ_z is strongly affected by the NP-QDs coupling factor. So, at locations where the coupling factor is negligible, σ_z tends to have the same amplitude of σ_0. However, when the detuning frequency Δ tends to be very small, the amplitude of the population difference is declined. This means that σ_{11} becomes close to σ_{22}. The interesting point in this regard is that by increasing the coupling factor (which means decreasing r), σ_z decreases in the broad area of the detuning frequency. Here, it is important to understand the behavior of the population difference, because it is a key factor to manipulate the NP's decay rate. Finally, to investigate the effect of the QDs on the NP decay rate, another simulation is carried out [Fig. 3(b)]. It is shown that the modified decay rate κ_m is strongly affected by the QDs' coupling strength whenever $\Delta \sim 0$. As shown in Fig. 3(a), in the vicinity of the NP,

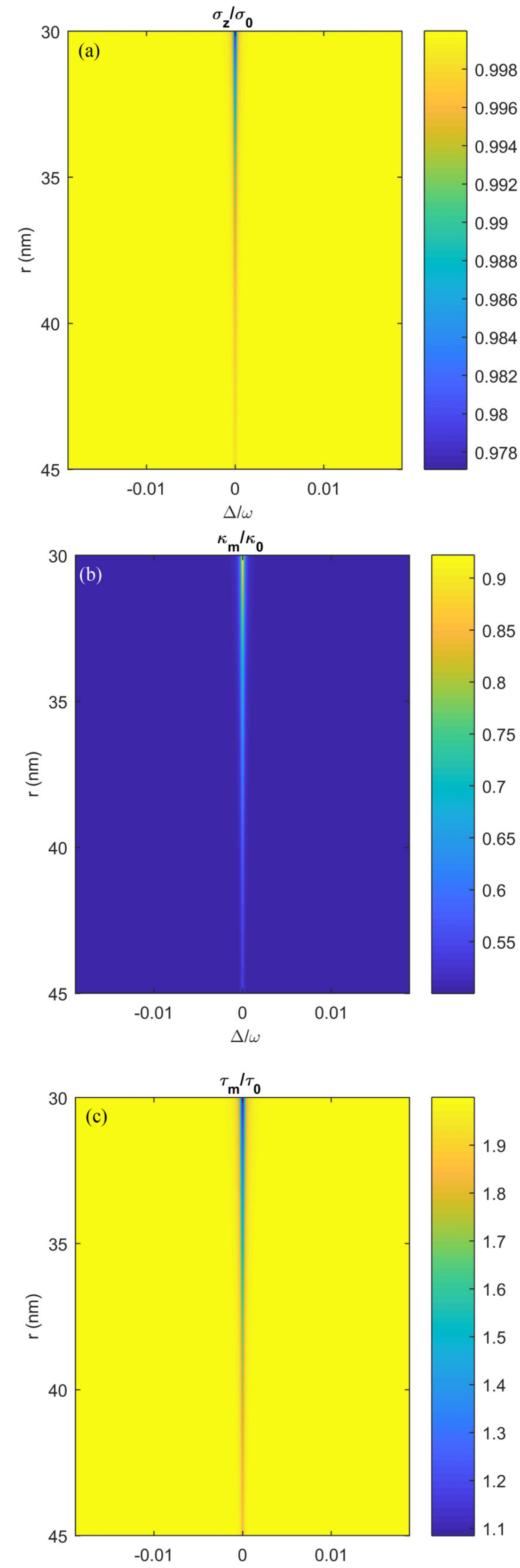

FIG. 3. (a) Population difference vs detuning frequency Δ/ω and QDs locations, (b) NP's modified decay rate as a function of detuning frequency Δ/ω and QD locations, (c) NP's modified lifetime as a function of detuning frequency Δ/ω and QD locations.

TABLE I. NP-QD coupled system assumed data.

κ_0	10^{13} 1/s
γ_{z0}	10^9 1/s
γ_{s0}	5×10^9 1/s
R_{NPs}	25 nm
R_{QDs}	3 nm
E_0	10^6 V/m
λ_{inc}	532 nm
σ_0	Variable
λ_{QDs}	532 nm

the population difference is changed. Therefore, at this area, the modified decay rate variation becomes great. This issue contributes to the coupling factor and population differences variation. To better estimate the effect of the QDs on the NP decay rate, another quantity known as NP lifetime $\tau_m = 1/\kappa_m$ is defined. The modified lifetime τ_m can tangibly illustrate the effect of the QDs coupled on NP. The normalized NP lifetime is calculated as τ_m/τ_0, where $\tau_0 = 1/\kappa_0$ [Fig. 3(c)]. It is readily seen that a QD coupling to the NP slightly alters the normalized NP lifetime just whenever $\Delta \sim 0$. That means that at other places where $\Delta \neq 0$, there is no alteration in the normalized NP lifetime, so $\tau_m/\tau_0 \sim 2$.

From the results illustrated in Fig. 3, it is predictable that the modified decay rate can be strongly altered by increasing the number of the coupled QDs to NP. This issue is the main goal followed in the present article. See Table I.

C. System with N QDs coupled to one plasmonic NP

Considering the schematic illustrated in Fig. 1, it is shown that the QDs are embedded at the shell region of the plasmonic NP, so, similarly, the system dynamics of motions (N QDs coupled to one NP) can be rewritten as

$$\begin{aligned} \dot{a} &= -(i\Delta + \kappa_0/2)a - i\sum_{j=1}^{N} g_j(r)\sigma_{-j} + \sqrt{\kappa_0}\varepsilon, \\ \dot{\sigma}_{-j} &= -(i\Delta_{ej} + \gamma_{s0})\sigma_{-j} + ig_j(r)a\sigma_{zj} - \Omega\sigma_{zj}, \end{aligned} \tag{6}$$

where N indicates the total number of QDs that are attached to the NP surface, and subscript j is the number of the present QDs. Therefore, we can rewrite the NP's modified decay rate when N QDs are embedded on the NP's surface as

$$\kappa_m = \kappa_0/2 - \sum_{j=1}^{N} g_j(r)^2\sigma_{zj} \Big/ (i\Delta_{ej} + \gamma_{s0}). \tag{7}$$

This equation indicates that by adding N QDs in the steady-state condition, the NP decay rate is strongly manipulated, which means that the induced dispersion losses by the plasmonic NPs are controllable.

After investigation of the effect of one QD on the NP's decay rate, we are now ready to study the effect of the N coupled QDs. Accordingly, the effect of the N QDs embedded at the hot-spot area on the NP's decay rate is investigated (Fig. 4) for six different numbers of the coupled QDs when $\sigma_0 = -1$. Moreover, for the sake of simplicity, it is supposed that all the coupled QDs have the same physical and optical characteristics, and are randomly distributed around the NP. In this figure, it is observed that at the points where $|\Delta| \gg 0$, the modified decay rate [Fig. 4(a)] and lifetime [Fig. 4(b)] are unchanged either in the vicinity or far away from the NP. In contrast, at $\Delta \sim 0$, the modified lifetime in Fig. 4(b) is dramatically changed by increasing the coupled QD numbers. For instance, $N = 40$ coupled QDs leads to a strong increase in the modified decay rate up to 7 times bigger than the initial amplitude. Also, in Fig. 4(b), it is observed that when the number of coupled QDs reaches $N = 40$, the modified lifetime declines and tends to zero. To illustrate clearly, the important sections of Figs. 4(a) and 4(b) are exaggerated and presented as the inset figures in Fig. 4. In the inset figures, one can exactly find how much the coupled QDs can manipulate the NP's lifetime. As a brief conclusion, it is shown that the plasmonic NP's decay rate is severely manipulated which, in essence, is the main reason to introduce the Ohmic losses in the plasmonic systems [18,19].

However, from Eq. (7), it is seen that changing the sign of σ_z leads to an increase in the lifetime of the plasmonic NP. This result is an important achievement to realize the fact that the loss introduced by the plasmonic NPs can be strongly restricted. For this reason, we supposed $\sigma_0 = +0.1$ and carried out some related simulations (Fig. 5). In this figure, it is observed that by increasing the coupled QDs on the NP's surface, the amplitude of the plasmonic NP's lifetime is strongly increased. Therefore, it suggests that in the coupling system, the plasmonic NP's decay rate depends on the coupling factor and more importantly on the QDs' population difference.

An achievement of this study is that one can design such core-shell NP-QDs to dramatically decrease the NP's dispersion losses. This effect can significantly improve the plasmonic applications in which the NP's induced thermal photons (having a disrupting effect on sensory applications [1,2,6]) are strongly restricted.

However, a more important question that can be asked about Eq. (7) is whether it is possible to have $\kappa_m \sim 0$ or $\kappa_m < 0$. To answer this question, we focus on the practical point of view. With regard to that point, κ_m cannot be zero. It is because a limited number of QDs can be attached on NP's surface, and more importantly, just a few of the attached QDs can be located in the hot-spot region. This means that all of the QDs attached on the NP's surface cannot be effectively coupled to the plasmonic field. In other words, in the experimental applications, it is impossible to have either $\kappa_m = 0$ or $\kappa_m < 0$.

In the following, one of the important features of this work is presented. It is notable that Eq. (7) is calculated in the steady-state condition in which the steady-state calculation of σ_{-j} from the second equation ($d\sigma_{-j}/dt$) of Eq. (6) is substituted in the first one (da/dt). However, to completely analyzing the system, Eq. (6) must be solved in the transient condition. For the sake of simplicity, we analytically solved a simplified version of Eq. (6) in which it is assumed that all QDs (N QDs) are embedded at the same location around the NP (not random). The time-dependent plasmonic mode $a(t)$

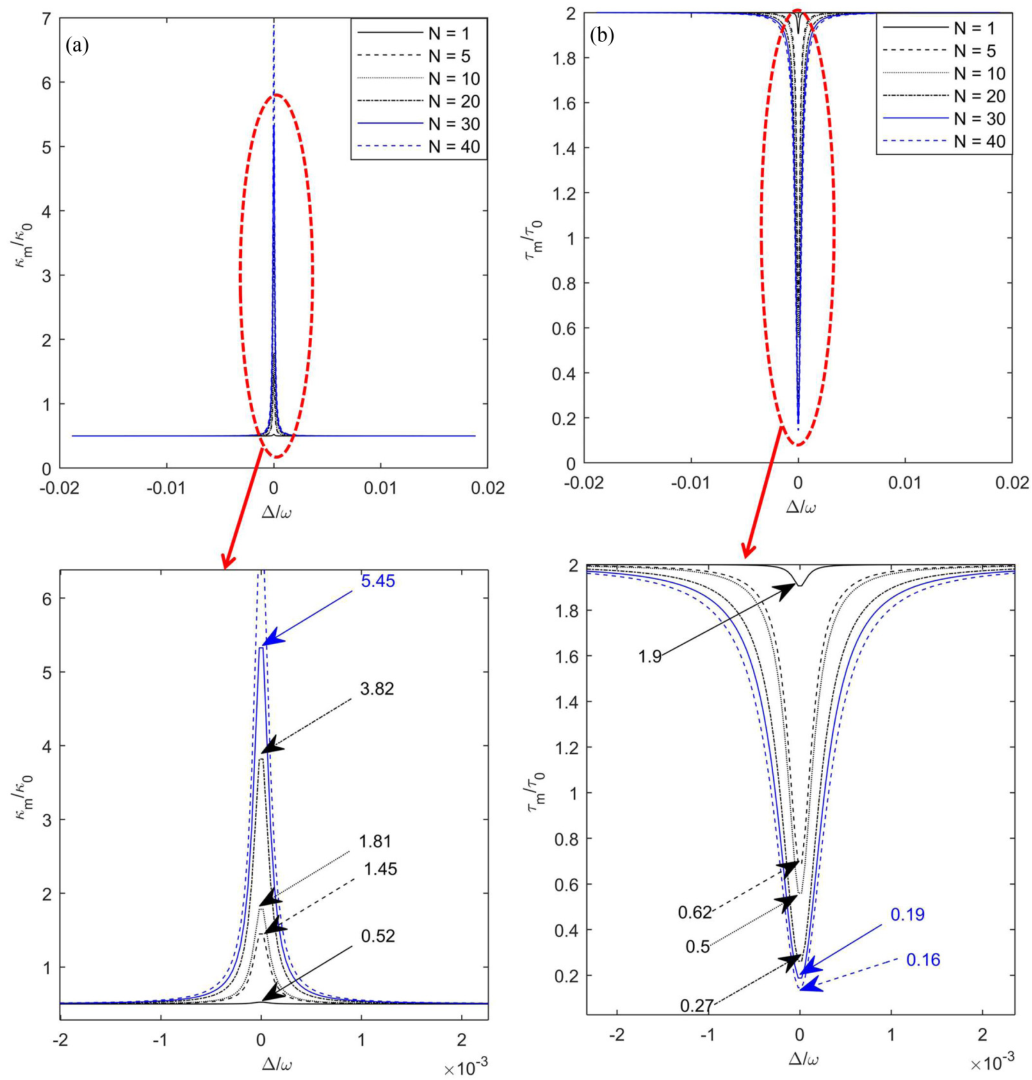

FIG. 4. QDs' coupling effect on (a) the NP's normalized modified decay rate (κ_m/κ_0) for $\sigma_z = -1$; (b) the NP's normalized lifetime (τ_m/τ_0) in the steady-state condition. To better illustrate, close-ups are shown in the lower row indicated by the red solid arrows.

is given by

$$a(t) = -\frac{i}{g(r)\sigma_z}\left[(i\Delta_e + \gamma_{s0}) - \frac{\kappa_{s1}}{2}\right]\left\{C_2 e^{[-0.5t\kappa_{s1}]} - \frac{i\left(\frac{M_1}{\kappa_{s1}} - 2i\Omega\sigma_z\right)}{2M_2}\right\}$$
$$-\frac{i}{g(r)\sigma_z}\left[(i\Delta_e + \gamma_{s0}) - \frac{\kappa_{s2}}{2}\right]\left\{C_1 e^{[-0.5t\kappa_{s2}]} + \frac{i\left(\frac{M_1}{\kappa_{s2}} - 2i\Omega\sigma_z\right)}{2M_2}\right\}, \quad (8)$$

where $\kappa_{s1} = (i\Delta + 0.5\kappa_0) + (i\Delta_e + \gamma_{s0}) + M_2$ and $\kappa_{s2} = (i\Delta + 0.5\kappa_0) + (i\Delta_e + \gamma_{s0}) - M_2$ which are the plasmonic mode decay rates after coupling in the transient condition. In other words, κ_{s1} manifests the effect of the plasmonic particles on the decay rate; κ_{s2} contributes to the QDs' influence. In these relations, $M_2 = \sqrt{\{(i\Delta + 0.5\kappa_0)^2 + (i\Delta_e + \gamma_{s0})^2 - 4(i\Delta + 0.5\kappa_0)(i\Delta_e + \gamma_{s0}) + 4N\sigma_z g(r)^2\}}$. This quantity, which directly affects κ_{s1} and κ_{s2}, shows the simultaneous effect of the NP-QDs' coupling factor, the QDs' population inversion, and the number of QDs coupled to the NP. The other factor is $M_1 = 2i\Omega\sigma_z\kappa_0 + 4\sigma_z g(r)\varepsilon\sqrt{\kappa_0}$, and also $C_1 = a(0)$ and $C_2 = \sigma_-(0)$ which are the plasmonic mode and population inversion initial value. Equation (8) suggests that the NP-QDs system decays with two decay rates constant. For example, if the system has no coupling effect between the NP and the QDs, $M_2 \sim 0.5\kappa_0$, which means that $\kappa_{s1} = 0.5\kappa_0$ and $\kappa_{s2} = \gamma_{s0}$. This fact shows that by changing the system parameters such as the NP-QDs' coupling strength and the number of QDs, one can manipulate the decay rates. It is satisfied with the contributed simulations in Figs. 4 and 5.

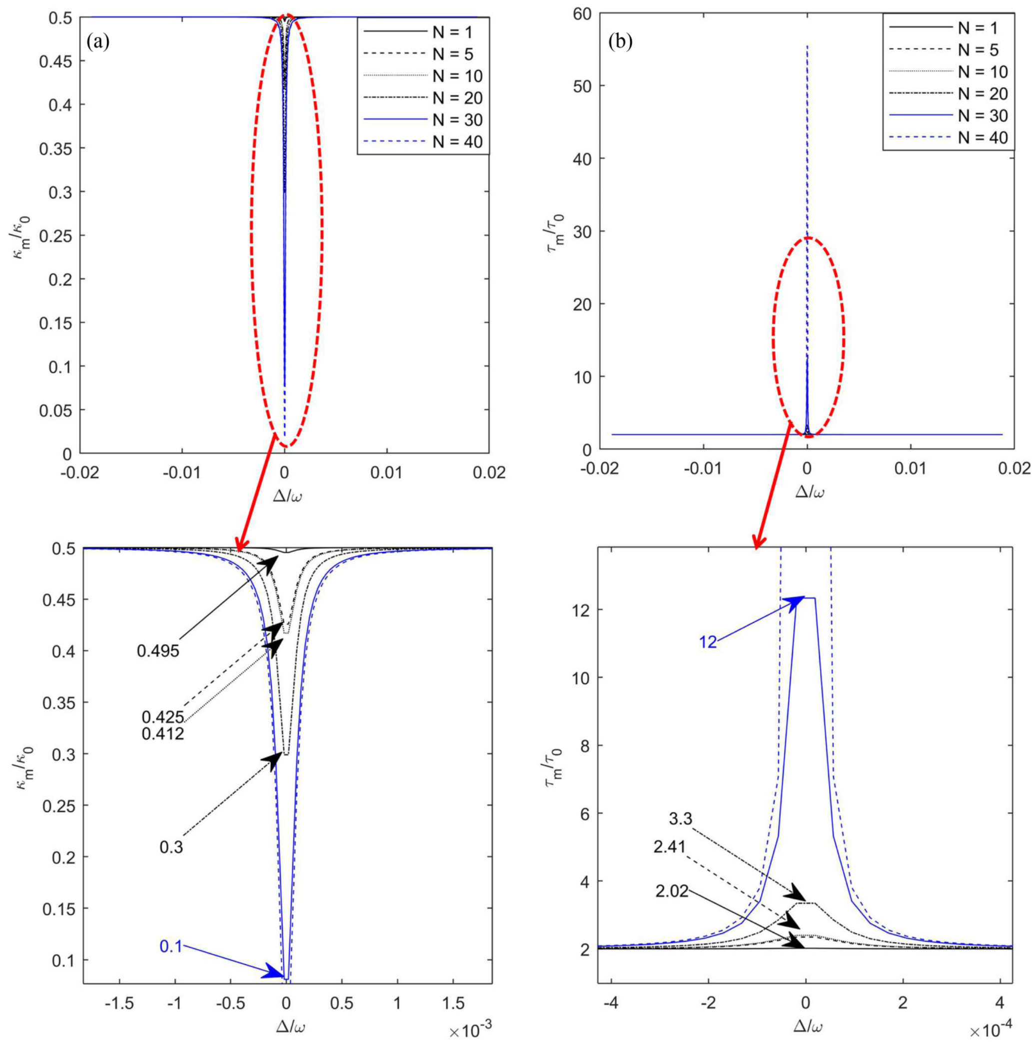

FIG. 5. QDs' coupling effect on (a) the NP's normalized modified decay rate (κ_m/κ_0) for $\sigma_z = 0.1$; (b) the NP's normalized lifetime (τ_m/τ_0) in the steady-state condition. To better illustrate, close-ups are shown in the lower row indicated by the red solid arrows.

Consequently, it is found that by coupling the small QDs embedded on the NP's surface, the decay rate of the plasmonic NP, which is the main reason to introduce the Ohmic losses, is effectively controlled. This suggests that, for instance, in quantum sensors [1,2,4,6,19,22], the generated thermal photon due to the plasmonic NP's decay effect can be strongly decreased. This is the important achievement of this study.

III. CONCLUSION

In this paper, the effect of N coupled QDs was investigated on the NP's decay rate in the steady-state and transient conditions. The dynamics of motion was studied by the Heisenberg-Langevin equations, followed by theoretically examining the influence of the coupled QDs on the NP's decay rate. As the most interesting conclusion of this study, it was theoretically shown how the coupled QDs on the NP's surface can modify the plasmonic mode decay rate. The results revealed that by coupling $N = 40$ QDs on a plasmonic NP surface in the steady-state condition, the contributed decay rate was strongly decreased. Of course, it was attained when the QDs' population difference is fixed to $\sigma_z = 0.1$. Accordingly, we showed that the NP's normalized lifetime (τ_m) was severely increased up to 50 times more than the initial value (τ_0). Moreover, we analyzed the effect of the QDs coupled on the NP's decay rate in the transient condition. For this purpose, we analytically solved the coupled equations and found that the plasmonic mode decays with two different rates when the coupling was established between the NP and the QDs. One of the decay rates, κ_{s1}, relates to the plasmonic particle effect and the other, κ_{s2}, contributes to the QDs' effect on the coupling system. Consequently, it was illustrated that the NP's decay rate can be decreased, and the amount of the decline can be controlled through the QDs' populations difference, NP-QDs' coupling strength, and the number of QDs embedded on the NP's surface.

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