Transport properties of a single plasmon interacting with a hybrid exciton of a metal nanoparticle–semiconductor quantum dot system coupled to a plasmonic waveguide

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Abstract
The transport properties of a single plasmon interacting with a hybrid system composed of a semiconductor quantum dot (SQD) and a metal nanoparticle (MNP) coupled to a one-dimensional surface plasmonic waveguide are investigated theoretically via the real-space approach. We considered that the MNP–SQD interaction leads to the formation of a hybrid exciton and the transmission and reflection of a single incident plasmon could be controlled by adjusting the frequency of the classical control field applied to the MNP–SQD hybrid nanosystem, the kinds of MNPs and the background media. The transport properties of a single plasmon interacting with such a hybrid nanosystem discussed here could find applications in the design of next-generation quantum devices, such as single-photon switching and nanomirrors, and in quantum information processing.

Keywords: surface plasmon, transport, quantum dot, metallic nanoparticle

(Some figures may appear in colour only in the online journal)

1. Introduction

Topics of light–matter interaction in physics have always been the focus for some fundamental investigations of photon–atom interaction and for its applications in quantum information, and its most elementary level is the interaction between a single photon and a single emitter [1, 2]. Photons could be regarded as ideal carriers of quantum information; therefore manipulating photons can have important applications in quantum information technology [3–5]. However, photons rarely interact with one another; thus we have to explore the ways to control photons with photon–atom interaction. Generally, photon–atom coupling in vacuum is usually very weak. However, we can modify this coupling strength by changing the environment of the vacuum by the Purcell effect [6]. Strong coupling of the interaction between a single photon and atoms could be achieved by confining the photon in reduced dimensions such as in a one-dimensional (1D) photonic waveguide with transverse cross sections on the order of a wavelength square [7]. There are several systems that can act as a 1D waveguide such as optical nanofibers [8], superconducting microwave transmission lines [9], photonic crystals with line defects [10] and surface plasmon nanowires [11]. Waveguides are extremely interesting,
because they can not only enhance the interaction but also guide the photon which is important for information transport. Recently, coherent control of single-photon (plasmon) transport has been the central topic in quantum information processing, and the idea of a single-photon transistor has also been reported [4].

The scattering of a single photon interacting with quantum emitters has been investigated in the real-space approach [12]. Quantum emitters can be various quantum systems such as two-level systems [12, 13], three-level systems [14, 15], and multiparticle systems [16, 17]. On the other hand, semiconductor quantum dots (SQDs) interacting with metal nanoparticles (MNPs) are now undergoing a period of explosive growth for their many applications, including those exploiting their optical properties such as a nonlinear Fano effect [18], controlling the Förster resonance energy transfer (FRET) between different SQDs [19], enhancing Rabi flopping in SQDs [20], etc. Note also that MNP–SQD systems have been studied for the formation of a tunable period of Rabi oscillation of excitons [21], nanoamplifier and nanopulse controller applications of MNPs [20], and field enhancement by plasmons [22]. Recently, it was shown that in MNP–SQD systems quantum decoherence can be controlled using a mid-infrared laser near-resonant with the conduction subbands of the SQD [23]. Among the various properties of an MNP–SQD hybrid system, we focus on the formation of hybrid excitons, the frequency of which is shifted from the bare exciton energy of the SQD. Previous theoretical investigations have mainly focused on the scattering of a single plasmon interacting with quantum emitters such as two- or multi-level systems, but not MNP–SQD hybrid systems. Hybrid MNP–SQD systems can combine the advantages of both materials for new applications and also provide us a variety of controllable ways for the transport of an incident single plasmon by adjusting several parameters such as the frequency of the classical control field applied, the kinds of MNPs and background media, the interparticle distances and the sizes of the nanoparticles. Motivated by these considerations, we investigate the scattering of a single plasmon interacting with an emitter coupled to a 1D surface plasmonic waveguide, where the emitter could be a hybrid MNP–SQD nanosystem. In the present paper, we propose a hybrid nanosystem consisting of an MNP and an SQD placed near the 1D surface plasmonic waveguide, which is a metal nanowire, and investigate theoretically the transport properties of a single incident plasmon interacting with such a hybrid MNP–SQD system.

2. Theoretical model and dynamics equations

We consider the scattering of an incident single plasmon interacting with a hybrid MNP–SQD system coupled to a 1D plasmonic waveguide; the schematic diagram of the system is exhibited in figure 1, where the hybrid system is composed of a spherical MNP of radius \( a \) and a spherical SQD with radius \( r \) in the presence of a polarized external field, \( E = E_0 \cos(\omega t) \). In this paper, the SQD is modeled as a spherical semiconductor with dielectric constant \( \varepsilon_s \), and a two-level atom-like quantum system at the center of it. We label the ground state (no exciton) of the SQD as level 1 and the excited state (one exciton) as level 2. This dielectric constant will produce a screening of the field incident on the SQD. We treat the exciton quantum mechanically in the density matrix formalism with exciton energy, \( \hbar \omega_0 = \varepsilon_2 - \varepsilon_1 \), and a transition dipole moment \( \mu \). We treat the MNP as a classical spherical dielectric particle with dielectric function \( \varepsilon_m \). For the description of the MNP, we use classical electrodynamics and the quasi-static approach. The center-to-center distance between the two nanoparticles is \( R \) (as shown in figure 1). The fundamental excitations in the MNP and in the SQD are surface plasmons with a continuous spectrum and discrete interband excitons, respectively. We suppose that there is no direct tunneling between the MNP and the SQD in the hybrid system and the MNP could not have direct interaction with the 1D surface plasmonic waveguide.

2.1. Hybrid exciton of MNP–SQD hybrid system

First of all, we discuss that the hybrid system of SQD–MNP leads to the formation of a new excitonic state with a transition frequency different from that of the bare exciton energy of the SQD. The Hamiltonian of the SQD in the hybrid system consisting of an MNP and a two-level SQD shown in figure 1 can be written as follows:

\[
\hat{H}_{\text{SQD}} = \sum_{i=1,2} \varepsilon_i \hat{c}_i^\dagger \hat{c}_i - \mu E_{\text{SQD}} \hat{c}_1^\dagger \hat{c}_2 - \mu E_{\text{SQD}}^* \hat{c}_2^\dagger \hat{c}_1, \tag{1}
\]

where \( \hat{c}_i^\dagger (\hat{c}_i) \) is the creation (annihilation) operator for the state of level \( i \) of the SQD. \( E_{\text{SQD}} \) is the total electric field felt by the SQD and consists of the classical control field, \( E = E_0 \cos(\omega t) \), and the induced internal field, produced by
the polarization of the MNP, $P_{\text{MNP}}$. In the dipole limit, $E_{\text{SQD}}$ can be written as $E_{\text{SQD}} = E + (s_0 P_{\text{MNP}}/4\pi\varepsilon_0 \varepsilon_{\text{eff}} R^2)$, where $\varepsilon_{\text{eff}} = (2\varepsilon_s + \varepsilon_a)/3\varepsilon_s$ and $\varepsilon_s$ is the dielectric constant of the background medium. $s_0 = 2(1)$ when the classical control field polarization is parallel (perpendicular) to the major axis of the hybrid system. The polarization $P_{\text{MNP}}$ comes from the charge induced on the surface of the SQD. It depends on the total electric field which is the superposition of the external field and the dipole field due to the SQD, $P_{\text{MNP}} = (4\pi \varepsilon_0 \gamma^2 |E + (s_0 P_{\text{MNP}}/4\pi\varepsilon_0 \varepsilon_{\text{eff}} R^2)|)$, where $\gamma = (\varepsilon_m (\omega_i) - \varepsilon_0)/(2\varepsilon_s + \varepsilon_m (\omega_i))$. We use the density matrix $\rho$ to calculate the polarization of the SQD, and then we have the ensemble average of the dipole moment. Using the off-diagonal elements of the density matrix, the dipole moment of the SQD can be written as $P_{\text{MNP}} = \mu (\rho_{21} + \rho_{12})$.

These matrix elements should be found from the master equation:

$$
\dot{\rho} = -\frac{i}{\hbar} [H_{\text{SQD}}, \rho] - \Gamma (\rho),
$$

where $\Gamma (\rho)$ is the relaxation matrix with entries $\Gamma_{ii} = \rho_{i2}/T_0$, $T_0 = 0.3 \text{ns}$, $\Gamma_{11} = (\rho_{12} - 1)/\tau_0$, $\Gamma_{22} = \rho_{22}/\tau_0$, $\tau_0 = 0.8 \text{ns}$. The relaxation time $\tau_0$ contains a contribution from nonradiative decay to dark states. By using the rotating wave approximations, we obtain the equations of motion for the density matrix as follows:

$$
\begin{aligned}
\dot{\rho}_{11} &= i\Omega \rho_{21} + iG \rho_{12} \rho_{21} - i\Omega^* \rho_{12} \\
&= -iG^* \rho_{12} + (\rho_{12} - 1)/\tau_0,
\end{aligned}
$$

$$
\begin{aligned}
\dot{\rho}_{22} &= -i\Omega \rho_{21} + iG \rho_{12} \rho_{21} + i\Omega^* \rho_{12} \\
&= +iG^* \rho_{12} + (1/\tau_0) \rho_{22},
\end{aligned}
$$

$$
\begin{aligned}
\dot{\rho}_{21} &= i(\omega_e - \omega_0) \rho_{21} + i\Omega^* \Delta + iG^* \rho_{21} \Delta - \frac{1}{T_{20}} \rho_{21},
\end{aligned}
$$

$$
\begin{aligned}
\dot{\rho}_{12} &= -i(\omega_e - \omega_0) \rho_{12} - i\Omega \Delta - iG \rho_{12} \Delta - \frac{1}{T_{20}} \rho_{12},
\end{aligned}
$$

where $\Delta = \rho_{11} - \rho_{22}$, $\Omega = \hbar E_0/(2\hbar)$, $\gamma = (s_0 \varepsilon_m (\omega_i) - \varepsilon_0)/(2\varepsilon_s + \varepsilon_m (\omega_i))$, and $\omega_0$ is the bare exciton frequency of an SQD, which could be decreased by the induced dipole moment $P_{\text{MNP}}$ of the MNP.

From the above equation, we can understand the meaning of the parameters $\Omega$ and $G$. Note that $G$ shows the interaction between the polarized SQD and the MNP. In other words, it is the dipole–dipole interaction term between the two nanoparticles. More exactly, $G$ arises when the classical control field polarizes the SQD, which in turn polarizes the MNP and then produces a field to interact with the SQD. It is proportional to $\mu^2$ rather than $\mu$ as for $\Omega$. Thus, this can be regarded as the self-interaction of the SQD, because this coupling to the SQD depends on the polarization of the SQD. On the other hand, $\Omega$ can be regarded as the normalized Rabi frequency associated with the external field and the field produced by the induced dipole moment $P_{\text{MNP}}$ of the MNP.

2.2. Single plasmon scattering by the MNP–SQD hybrid system

Now, we investigate the scattering properties of a single plasmon interacting with the MNP–SQD hybrid system. We regard the MNP–SQD hybrid system as a new single SQD, and the exciton frequency of which can be controlled by adjusting the parameter $G = s_0^2 \gamma^2 \mu^2/(4\pi\varepsilon_0 \varepsilon_{\text{eff}} R^2)$. We use a real-space Hamiltonian to treat the coherent surface-plasmon transport in the nanowire coupled to the hybrid MNP–SQD nanosystem. Under the rotating wave approximation, the Hamiltonian of the hybrid system in real space can be written as [12].

$$
H = (\omega_2 - i\Omega^*)/2 \sigma_{22} + \omega_1 \sigma_{11} + iv_2
$$

$$
\times \int_{-\infty}^{\infty} dz \{a^+_1 (z) \partial_z a_1 (z) - a^+_2 (z) \partial_z a_2 (z)\}
$$

$$
+ g \{[a^+_1 (z) + a^+_2 (z)] \sigma_{12} + [a_1 (z) + a_2 (z)] \sigma_{21}\}
$$

(5)

Here, $\omega_1$ and $\omega_2$ are the eigenfrequencies of the ground state $\langle 11 \rangle$ and the excited state $\langle 22 \rangle$ of the hybrid exciton, respectively, and $\omega_{\text{pq}}$ is the frequency of the incident surface plasmon with wavevector $k$ ($\omega_{\text{pq}} = v_{\text{pq}} k$). $\sigma_{12} = [1, 2]$ $\sigma_{21} = [2, 1]$ is the lower (raising) operator of the hybrid exciton, and $a^+_i (z)$ ($a^+_i (z)$) is the bosonic operator creating a right-going (left-going) plasmon at position $z$ of the hybrid exciton. $v_2$ is the group velocity corresponding to $\omega_{\text{pq}}$, and the non-Hermitian term in $H$ describes the decay of state $12$ at a rate $\Gamma_2$ into all other possible channels, where $\Gamma_2 = \Gamma_1 - G_1$ is the decay rate of the hybrid exciton (where $\Gamma_1$ is a decay rate of the bare exciton).

$g = 2\pi \hbar/(\omega_{\text{pq}})^{1/2} \omega_{\text{hybrid}} D \cdot e \sigma$ is the coupling constant of the hybrid exciton with a single plasmon, where $\omega_{\text{hybrid}} = \omega_{\text{pq}} - G_2$ is the resonance energy of the hybrid exciton, $D$ is the dipole moment of the hybrid exciton, and $e \sigma$ is the polarization unit vector of the surface plasmon [12]. The Hamiltonian includes three parts. The first term describes the hybrid exciton, the second term describes propagating single plasmons which run in both directions and the third term describes the interaction between the hybrid exciton and the single propagating plasmon. The eigenstate of the system considered, defined by $H \psi_{zk} = E_k \psi_{zk}$, can be
constructed in the form
\[ |\psi_k\rangle = \int dz [\phi_{s,p}^+(z) a_i^+(z) + \phi_{b,i}^+(z) a_i^+(z)] \times |0, 1\rangle + \epsilon_i |0, 2\rangle \] (6)

where \(|0, 1\rangle\) denotes the vacuum state with zero plasmon and the hybrid exciton unexcited, \(|0, 2\rangle\) denotes the hybrid exciton in the excited state and \(\epsilon_i\) is the probability amplitude of the exciton in the excited state. \(\Phi_s(z)(\Phi_{b,i}(z))\) is the wave-function of a right-going (left-going) plasmon at position \(z\).

Now, we can solve the Schrödinger equations by substituting equation (6) into equation (5), which results in the following relations:
\[ t = \frac{[\omega_0 - \omega_{sp} - \omega_R]}{[\omega_0 - \omega_{sp} - \omega_R] - i(\Gamma_z^2/2 + J)} \] (7)
\[ r = \frac{iJ}{[\omega_0 - \omega_{sp} - \omega_R] - i(\Gamma_z^2/2 + J)} \] (8)

where \(J = g^2/v_F\). Therefore, we can control the transferring properties of an incident single plasmon by changing the coupling mechanism of the hybrid exciton of the MNP–SQD nanosystem, such as the dielectric constants of the background medium \(\epsilon_b\), the frequency of the classical control field \(\omega_c\), the frequency of the incident single plasmon \(\omega_{sp}\), the size of the SQD or MNP \((r \text{ or } a)\), the interparticle distance between the MNP and SQD \((R)\), the polarization of the classical control field \(\epsilon_{b}\), the transition frequency of the SQD \(\omega_b\), etc.

3. Theoretical analysis and numerical results

The scattering properties of a single plasmon in a long time limit can be characterized by the transmission (reflection) coefficient, \(T = |t|^2 \text{ ( } R = |r|^2\). Firstly, we investigate the influence of the frequency of the classical control field on the formation of a hybrid exciton in the MNP–SQD hybrid nanosystem as shown in figure 1. We note that \(G_R\) and \(G_I\) provide us with key information regarding the exciton–surface coupling effect in the MNP–SQD hybrid system. As we mention above, for a weak laser field, the imaginary part of \(G\) represents the FRET rate from the SQD to the MNP and therefore contributes to the damping rate of the SQD. The real part of \(G\) refers to the red-shift of the SQD transition caused by the plasmonic effects.

Figure 2 shows the the dependence of the parameter \(G\) on the frequency of the classical control field with different values of the dielectric constants of the background medium. In our calculations, we take the transition frequency of the SQD as 3 eV and the radius of the MNP as 7 nm. We also take the polarization of the classical control field parallel to the axis of our MNP–hybrid system, \(\epsilon_{b} = 1\). Figures 2(a) and (b) show the imaginary part and real part of \(G\) versus the frequency of the classical control field, respectively. As we can see easily from figure 2(a), there appears a single peak near the value \(\omega_c = 3\) eV when \(\epsilon_{b} = 1\). We can also find that the maximum value of \(G_I\) increases as the value of the dielectric constant of the background medium decreases, resulting in the enhancement of the FRET rate from the SQD to the MNP. From figure 2(b), we see the Fano-like line shape near the value \(\omega_c = 3\) eV when \(\epsilon_{b} = 1\). As the dielectric constants of the background medium increase, the height of the peaks decreases and the positions of the peaks move to the left, where the positive peak results in a red-shifted frequency of the hybrid exciton from that of the bare exciton and the negative peak results in a blue-shifted frequency. Figure 2(c) shows the dependence of the frequency of the hybrid exciton on the frequency of the classical control field with different dielectric constants of the background, where the negative peak corresponds to a red-shift and the positive peak to a blue-shift of the transition frequency of the hybrid exciton in the MNP–SQD hybrid system. We can also evaluate the range of the frequency of the hybrid exciton from figure 2(c); for example, the hybrid exciton has frequency in the range between \(\omega_{hybrid} = 2.999\) 49 eV (the minimum value in the negative peak) and \(\omega_{hybrid} = 3.000\) 50 eV (the maximum value in the positive peak) when \(\epsilon_{b} = 3\), \(\omega_0 = 3\) eV. The above results suggest that one can control the transport properties of an incident single plasmon interacting with such
a hybrid nanosystem by adjusting the electric constants of the environment and the frequency of the classical control field.

Figure 3 shows the transmission properties of a propagating single plasmon interacting with the MNP–SQD hybrid system as a function of the frequency of the classical control field. We take the frequencies of the bare exciton and the incident plasmon to be equal to 3 eV, respectively. Under the above conditions, the transmission of a single incident plasmon exhibits a double-peak transmission curve, in the mid point of which there appears a complete reflection peak when $\varepsilon_e = 1$. As the dielectric constant of the background medium increases, the complete reflection peak moves to the left with an unchanged line shape (figures 3(a) and (b)). As we can see from figure 3(a), for example, the switching of single-plasmon transport could be accomplished in the range between $\omega_p = 2.97\text{ eV}$ (the minimum value in the negative peak in figure 2(c)) and $\omega_c = 3.03\text{ eV}$ (the maximum value in the positive peak in figure 2(c)) when $\varepsilon_e = 3$. From figure 3(b), we can see that the complete transmission disappears when $J = 5 \times 10^{-8} \omega_0$ and there exists a complete reflection peak between the two peaks of transmission. This means the transmission of a single plasmon interacting with an MNP–SQD hybrid system could be depressed largely because of the coupling between the hybrid system and the plasmonic waveguide. Figure 3(c) shows that the complete reflection disappears when $G_1 = 0$.

Now, we can consider the transmission spectra of a single plasmon interacting with the MNP–SQD hybrid system versus the incident frequency of the single surface plasmon (figure 4). Figure 4(a) shows intuitively the influence of the formation of the hybrid exciton in the MNP–SQD hybrid system on the scattering properties of an incident single plasmon, where subscripts 1, 2 and 3 correspond to the three different frequencies of the hybrid exciton, $\omega_{\text{hybrid}} = 2.99949\text{ eV}$, $\omega_{\text{hybrid}} = 3\text{ eV}$ and $\omega_{\text{hybrid}} = 3.00050\text{ eV}$, respectively. Figure 4(b) shows the transmission and reflection spectra of a propagating plasmon interacting with the hybrid system when there exists FRET from the SQD to the MNP, from which we can see that the complete reflection peak disappears. In fact, when $\text{Im}[G] \neq 0$, there exists a FRET rate from the SQD to the MNP, which contributes to the decay rate of the SQD, resulting in the leakage of energy. In other words, a decay rate of the hybrid exciton could be different from that of the bare exciton, thus resulting in the disappearance of the complete reflection peak.

Next, we discuss the influence of the dielectric constants of the background on the formation of the hybrid exciton and the resonant frequency of the hybrid exciton. Figures 5(a) and (b) show the imaginary part and real part of $G$ versus the frequency of the classical control field, respectively, where the height of the peak is increased and the position of the peak moves to the left as the frequency of the classical control field increases. Figure 5(b) shows the real part of $G$, with the Fano-like line shape, which refers to the frequency shift of the SQD transition caused by the plasmonic effects. The real part of $G$ has its maximum at $\varepsilon_e = 2.93$ in the positive peak and its minimum at $\varepsilon_e = 3.07$ in the negative peak, for example, when $\omega_c = 3\text{ eV}$, which results in a red-shifted and blue-shifted frequency of the hybrid exciton, respectively. We confirm the above results from figure 5(c), from which one can see the range of frequencies of the hybrid exciton. For example, when $\omega_c = 3\text{ eV}$, the frequency of the hybrid exciton could have values between $\omega_{\text{hybrid}} = 2.99948\text{ eV}$ and $\omega_{\text{hybrid}} = 3.00049\text{ eV}$, which correspond to $\varepsilon_e = 2.93$ and $\varepsilon_e = 3.07$, respectively.

Figure 6 shows the transmission spectra of a single propagating plasmon interacting with the hybrid system as a function of the dielectric constant of the background medium with different frequencies of the classical control field. From figure 6(a), we can see that appropriately adjusting the dielectric constant of the background and the frequency of the classical control field results in the switching of the transport of a single propagating plasmon, which is quite different from previous results [12, 16]. For example, there appear two complete transmission peaks at $\varepsilon_e = 2.93$ and $\varepsilon_e = 3.07$, respectively, even when $\omega_0 = 3\text{ eV}$, $\omega_{\text{ip}} = 3\text{ eV}$. The
Figure 4. The transmission and reflection spectra of a propagating single plasmon interacting with the hybrid system versus the incident frequency of the single surface plasmon: (a) without dissipation ($G_1 = 0$) and (b) with dissipation ($G_1 = 0$). Here, the dashed line (dotted line), solid (dash-dot-dotted line) and dash-dotted (short dash-dotted line) are the transmission (reflection) spectra, corresponding to the frequency of the hybrid exciton, $\omega_{\text{hybrid}} = 2.999 \, 49 \, \text{eV}$, $\omega_{\text{hybrid}} = 3 \, \text{eV}$ and $\omega_{\text{hybrid}} = 3.000 \, 50 \, \text{eV}$, respectively. In all cases, $\varepsilon_0 = 3$, $\varepsilon_a = 6$, $\omega_0 = 3 \, \text{eV}$, $a = 7 \, \text{nm}$, $\mu = 10^{-28} \, \text{C m}$, $R = 13 \, \text{nm}$ and $J = 5 \times 10^{-5} \omega_0$.

Figure 5. The influence of the exciton–surface plasmon coupling effect on the formation of the hybrid exciton and the resonant frequency of the hybrid exciton versus the dielectric constants of the background when the distance between the MNP and the SQD is $R = 13 \, \text{nm}$. (a) The imaginary part of $G$ (b) the real part of $G$ and (c) the resonant frequency of the hybrid system composed of a metallic nanoparticle and an SQD. Here $\omega_0 = 3 \, \text{eV}$, $a = 7 \, \text{nm}$, $\mu = 10^{-28} \, \text{C m}$ and $\omega = 2.5 \, \text{eV}$, $3 \, \text{eV}$, $3.5 \, \text{eV}$, which correspond to the dash-dotted line, the solid line, and the dashed line, respectively.

Figure 6. The transmission spectra of a propagating plasmon interacting with the hybrid system versus the dielectric constants of the background, where $\varepsilon_0 = 6$, $\omega_0 = 3 \, \text{eV}$, $\omega_{\text{sp}} = 3 \, \text{eV}$, $a = 7 \, \text{nm}$, $\mu = 10^{-28} \, \text{C m}$ and $R = 13 \, \text{nm}$; (a) $J = 5 \times 10^{-4} \omega_0$ ($G_1 = 0$), (b) $J = 5 \times 10^{-4} \omega_0$ and (c) $J = 5 \times 10^{-5} \omega_0$ ($G_1 \neq 0$). Here, the solid line, dashed line and dash-dotted line correspond to $\omega_c = 3 \, \text{eV}$, $3.5 \, \text{eV}$, $2.5 \, \text{eV}$, respectively.
controllable transport properties of a single plasmon via the changing of the dielectric constant of the background provide us a way to construct the light switch. Figure 6(b) shows the transmission spectra of the single plasmon when the coupling strength between the MNP–SQD hybrid system and 1D plasmonic waveguide is $5 \times 10^{-4} \omega_0$, from which one can see that the transmission of a single plasmon interacting with such a hybrid system could be depressed largely because of the coupling between the hybrid system and the plasmonic waveguide. In the case of considering the dissipation of the hybrid system, the height of the double-peak of transmission is less than 1 and the complete reflection disappears.

Based on the results shown in figure 5, we illustrate the transport properties of a single propagating plasmon via the incident frequency of the single plasmon (figure 7). Figure 7(a) shows the transmission and reflection spectra of the single plasmon when the frequency of the classical control field is equal to the natural frequency of the SQD, $\omega_c = 3$ eV. As we can see from figure 7(a), one can control the switching of an incident single plasmon with certain frequencies, at which the single plasmon can be perfectly reflected, by adjusting the frequency of the classical control field and properly selecting the background media. Figure 7(b) shows the effect of dissipation on the transmission and reflection spectra. Clearly, complete transmission could not be obtained even near the frequency of the hybrid exciton. In the meantime, the maximum value of the reflection coefficient is dramatically decreased and the width of the line shape is broadened. We can also find that the summation of the transmission coefficient and reflection coefficient is always less than 1, which implies that the incident single plasmon undergoes an inelastic scattering process. We can explain this result as follows: when $G_1 = 0$, there exists a FRET rate from the SQD to the MNP, which contributes to the damping rate of the SQD, resulting in the leakage of energy. Therefore, the energy of the incident single plasmon is not conserved before and after the scattering happens—the scattering is obviously inelastic. The inelastic scattering process would broaden the width of the line shape. This decoherence mechanism would reduce the quantum switching efficiency.

Finally, we investigate the influence of the kind of MNPs on the formation of a hybrid exciton in the MNP–SQD nanosystem (figure 8). Figures 8(a) and (b) show the imaginary part and real part of $G$, respectively, where we select three kinds of MNPs—namely, Au, Ag, and Cu. As shown in figure 8(a), for the parameters considered in this paper, the imaginary parts of $G$ peak at 3 eV, 3.035 eV and 2.935 eV, corresponding to Au, Ag, and Cu, respectively. In particular, the height of the peak for Ag is much greater than the others, which implies that the FRET rate from the SQD to the Ag MNP is much greater than that to the Au MNP or Cu MNP. Similarly, the real part of $G$ presents a positive peak and a negative peak for a given material of MNP, where the height of the peaks for Ag is noticeably greater than the others. Figure 8(c) shows the dependence of the frequency of the hybrid exciton versus the frequency of the classical control field with various kinds of metals—namely, Au, Ag and Cu. As we can see from figure 8(c), the changeable range of frequency of the hybrid exciton for the Ag MNP is much wider than that for Au or Cu MNPs, which suggests that a way to coherently control the transport of a single plasmon (photon) in the wide-band frequency region is by selecting an appropriate material of MNPs.

Several remarks concerning the experimental realizations for the scheme proposed in this paper should be addressed here. At the device level, the results studied in this paper can be utilized in such a way that SQDs can be attached to a metallic nanowire. The MNP is attached to a sharp optical fiber tip. An atomic force microscope could be used to probe the tip and stabilize its distance [24]. In those schemes, quantum coherence could be generated by an incident laser beam, while the signal is launched through the nanowire as a
and propagating plasmon, as shown in [25]. Recently, the first experimental demonstration of plasmon–exciton coupling between a silver nanowire and a pair of SQDs was reported [26], where the interparticle distance between the two SQDs ranges from microns to 200 nm within the diffraction limit and parameters including the surface plasmon’s propagation length and the wire terminal reflectivity are experimentally determined. Dissipative processes cannot be avoided in real systems. The quantum noise in nonwaveguide modes would destroy some of the interference effects found in this paper. We hope to address the decoherence issues in the near future.

4. Conclusions

In conclusion, we proposed a new hybrid system, an MNP–SQD hybrid system placed near a 1D plasmonic waveguide, and theoretically investigated the transport properties of a single plasmon interacting with such an MNP–SQD hybrid nanosystem. We showed that the plasmonic effects on the SQD give rise to the formation of a hybrid exciton, thus resulting in the coherent control of the transport of an incident single plasmon interacting with such a hybrid system by adjusting the dielectric constant of the background medium, the frequency of the classical control field, the coupling between the hybrid exciton and plasmonic waveguide, and the kind of MNP. Our results show that the transport properties of a single plasmon interacting with such a hybrid exciton formed in the MNP–SQD hybrid system could be quite different from those of a bare exciton in a single SQD, giving us comparatively rich ways to control the transport of a single plasmon based on the exciton–plasmon coupling effect. The results discussed in this paper could find a variety of applications in the design of quantum optical devices, such as quantum switches and nanomirrors, and in quantum information processing.

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