Controlling Fano resonance of nanowire surface plasmons

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We theoretically study the effect of the applied magnetic field on the scattering properties of the nanowire surface plasmons coupled to two quantum dots. The dispersion relations of the surface plasmon are found to be upwardly displaced in the presence of an applied magnetic field. The symmetric double peaks in the transmission spectrum resulting from the interference between the localized and delocalized channels of the surface plasmon can combine together and the associated Fano lineshape will be smeared out when increasing the magnitude of the magnetic field.

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With tunable luminescence properties like broad excitation spectrum, narrow emission spectrum, and size-dependent emission [1], quantum-dot (QD) has attracted much attention recently for being an excellent single-photon source [2] and for its ability to act as photon detectors [3].

When a light wave strikes a metal surface, a surface plasmon (SP) polariton can be excited [4]. Investigations of the nonlinear dispersion relations of nanowire SPs have been reported [5,6]. Recently, great attention has been focused on the so-called plasmonics, since SPs reveal strong analogies to light propagation in conventional dielectric components [7]. With the development of technologies, a coupled system comprising of a single metal nanowire with a QD has been fabricated successfully [8,9]. This leads to the possibilities of investigating cavity quantum electrodynamics [5,6,10,11] and coherent single SP transport [12–16] within such a device. The nonlinear behavior of the dispersion relations of the nanowire SPs can also be used to observe the Fano resonance, which is originated from the interference between the localized and delocalized channels [17–20].

Inspired by these work, in this Letter, we study the effect of the magnetic field on the QD plasmon system. We find the dispersion relations of the nanowire SPs can be controlled by the magnetic field. This brings a possible way to vary the coupling strength between QDs and SPs instead of tuning the exciton energy of the QD. We further find that,by appropriately tuning the magnitude of the magnetic field, one can control the presence of the Fano resonance.

The system we consider here is composed of two QDs with exciton energy $\hbar\Omega_j$ ($j = 1$ and 2), separated by a distance d, both coupled to a silver nanowire with coupling strength g_j, as depicted in Fig. 1. A constant magnetic field H_0 is applied along the axial direction (z-axis) of the nanowire. The dielectric tensor in the presence of a constant magnetic field can be expressed as [21]:

$$\epsilon = \begin{bmatrix} \epsilon_{1,j} & -i\epsilon_{2,j} & 0 \\ i\epsilon_{2,j} & \epsilon_{1,j} & 0 \\ 0 & 0 & \epsilon_{3,j} \end{bmatrix}, \qquad (1)$$

where $j = \mathrm{I}$ (II) denotes the region inside (outside) the wire. For $j = \mathrm{I}$, $\epsilon_{1,\mathrm{I}} = \epsilon_\infty[1 + \omega_p^2/(\omega_c^2 - \omega^2)]$, $\epsilon_{2,\mathrm{I}} = \epsilon_\infty[\omega_c\omega_p^2/\omega(\omega_c^2 - \omega^2)]$, and $\epsilon_{3,\mathrm{I}} = \epsilon_\infty(1 - \omega_p^2/\omega^2)$. For $j = \mathrm{II}$ (the free space), $\epsilon_{1,\mathrm{II}} = \epsilon_{3,\mathrm{II}} = 1$, and $\epsilon_{2,\mathrm{II}} = 0$. Here, $\omega_p = (4\pi\rho_e e^2/m_e^*\epsilon_\infty)^{1/2}$ is the plasmon frequency, $\omega_c = eH_0/m_e^*$ is the cyclotron frequency, and ω denotes the frequency of the SP. Where ρ_e is the charge density, m_e^* is the effective mass, e is the electric charge, and ϵ_∞ is the high-frequency dielectric constant of the material.

The components of the electromagnetic wave of the n-mode SPs can be obtained by solving the Maxwell's equations with appropriate boundary conditions. Furthermore, by applying the continuity conditions of the electromagnetic fields at the interface, the transcendental equation $S(k_z, \omega) = 0$ can be obtained:

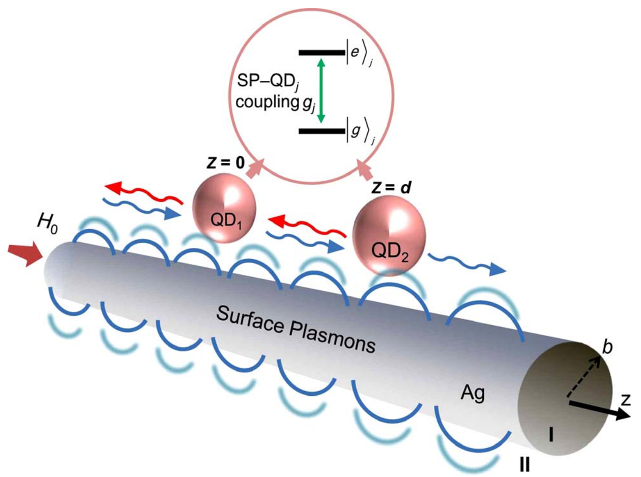

Fig. 1. (Color online) Schematic diagram of two QDs coupled to a silver nanowire with an applied magnetic field (H_0) along the z-direction. Here, b is the radius of the nanowire.

$$
\begin{aligned}
S(k_z,\omega) = {} & \frac{c^2}{\zeta_{\mathrm{I}}^2\zeta_{\mathrm{II}}^2 b^2}\{(nck_z)^2\mathfrak{I}_{n,E}\mathfrak{I}_{n,H}\mathfrak{K}_n^2[(\eta_{\mathrm{II}}\zeta_{\mathrm{I}}-\eta_{\mathrm{I}}\zeta_{\mathrm{II}})^2 \\
& -\omega^4\epsilon_{2,\mathrm{I}}^2\zeta_{\mathrm{II}}^2]+b\omega^2[\zeta_{\mathrm{II}}K_{\mathrm{I}}^E\mathfrak{K}_n\mathfrak{I}'_{n,E} \\
& \times[-n\epsilon_{2,\mathrm{I}}\mathfrak{I}_{n,H}\mathfrak{K}_n[c^2k_z^2(\eta_{\mathrm{II}}\zeta_{\mathrm{I}}-\eta_{\mathrm{I}}\zeta_{\mathrm{II}})+\omega^2\xi_{\mathrm{I}}\zeta_{\mathrm{II}}] \\
& +b\zeta_{\mathrm{II}}K_{\mathrm{I}}^H\mathfrak{K}_n\mathfrak{I}'_{n,H}(\omega^2c^2k_z^2\epsilon_{2,\mathrm{I}}^2-\xi_{\mathrm{I}}\eta_{\mathrm{I}}) \\
& +bK_{\mathrm{II}}\xi_{\mathrm{I}}\eta_{\mathrm{II}}\zeta_{\mathrm{I}}\mathfrak{I}_{n,H}\mathfrak{K}'_n]+\zeta_{\mathrm{I}}\mathfrak{I}_{n,E}[K_{\mathrm{I}}^H\zeta_{\mathrm{II}}\mathfrak{K}_n\mathfrak{I}'_{n,H} \\
& \times(bK_{\mathrm{II}}\xi_{\mathrm{II}}\eta_{\mathrm{I}}\mathfrak{K}'_n-(nck_z)^2\epsilon_{2,\mathrm{I}}\eta_{\mathrm{II}}\mathfrak{K}_n) \\
& +K_{\mathrm{II}}\mathfrak{I}_{n,H}\mathfrak{K}'_n[n\epsilon_{2,\mathrm{I}}\zeta_{\mathrm{II}}\mathfrak{K}_n(c^2k_z^2\eta_{\mathrm{II}}+\omega^2\xi_{\mathrm{II}}) \\
& -bK_{\mathrm{II}}\xi_{\mathrm{II}}\eta_{\mathrm{II}}\zeta_{\mathrm{I}}\mathfrak{K}'_n]]]\}=0, \qquad (2)
\end{aligned}
$$

where $K_{\mathrm{I}}^E=(1/c)(|\epsilon_{3,\mathrm{I}}\zeta_{\mathrm{I}}/\xi_{\mathrm{I}}|)^{1/2}$, $K_{\mathrm{I}}^H=(|\zeta_{\mathrm{I}}/c^2\eta_{\mathrm{I}}|)^{1/2}$, $K_{\mathrm{II}}^E=K_{\mathrm{II}}^H=K_{\mathrm{II}}=(|(\omega^2/c^2)-k_z^2|)^{1/2}$, $\eta_j=c^2k_z^2-\epsilon_{1,j}\omega^2$, $\zeta_j=c^4k_z^4-2\epsilon_{1,j}c^2k_z^2\omega^2+(\epsilon_{1,j}^2+i\epsilon_{2,j}^2)\omega^4$, $\xi_j=\epsilon_{1,j}c^2k_z^2-(\epsilon_{1,j}^2+i\epsilon_{2,j}^2)\omega^2$, and $\mathfrak{I}_{n,E(H)}(K_{\mathrm{I}}^{E(H)}\rho)$ $[\mathfrak{K}_n(K_{\mathrm{II}}\rho)]$ is the n-th mode modified Bessel function inside (outside) the nanowire with ρ being the radial coordinate. Here, capital index E (H) denotes the electric (magnetic) field and b is the radius of the nanowire. The dispersion relations of SPs can then be obtained by finding the roots of the transcendental equation [Eq. (2)].

Figure 2(a) shows the dispersion relations for different modes ($n=0\sim3$) of SPs without the magnetic field. In our previous work [6], we found that it is possible to make the QDs coupled to only $n=0$ and one mode of the SPs by choosing the exciton energy appropriately. Since the $n=1$ mode of the SPs dominates for thin nanowires [6], we can therefore legitimately focus on the $n=1$ mode in the following discussions. Figure 2(b) shows the dispersion curves around the local minimum for the $n=1$ mode of SPs in the presence of different

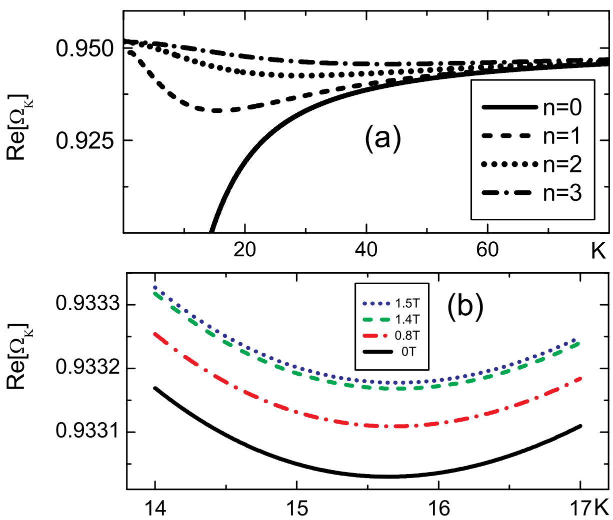

Fig. 2. (Color online) (a) Dispersion relations of the nanowire SPs in the absence of the magnetic field for $n=0\sim3$ modes. Here, the radius $b=0.1$ and one unit of b is equal to 53.8 nm. (b) The dispersion relations of $n=1$ mode for the magnetic field $H_0=0$ (black-solid), 0.8 (red-short-dash-dotted), 1.4 (green-dashed), and 1.5 (blue-dotted) T. The units of the frequency and the wavevector of the nanowire SPs are normalized by the plasma frequency ω_p: $\Omega_K=\omega/\omega_p$ and $K=k_zc/\omega_p$ with c being the speed of light.

magnitudes of the magnetic field. As seen in Fig. 2(b), the magnetic field produces the cyclotron frequency and the dispersion curve is upwardly displaced when increasing the magnitude of the magnetic field. This indicates that, with the applied magnetic field, one can reduce or enlarge the detuning $(\hbar\Omega_j-\omega_k)$ between QDs and SPs, such that the coupling strength between QDs and SPs can be varied by tuning the magnitude of the applied magnetic field.

In order to investigate how the applied magnetic field affects the scattering properties of the SPs, we further study the stationary scattering of the system with a SP carrying energy $E_k=\hbar\omega_k$ incident from the left end of the silver nanowire. In the presence of the magnetic field, the Hamiltonian can be described as [12,22]:

$$
\begin{aligned}
H = {} & \sum_k \hbar\omega_k a_k^\dagger a_k + \sum_{j=1,2}\hbar\Omega_j\sigma_{e_j,e_j} \\
& + \sum_k\sum_{j=1,2}\hbar g_j[a_k e^{ik(j-1)d}\sigma_{e_j,g_j}+\mathrm{H.c.}], \qquad (3)
\end{aligned}
$$

where $a_k^\dagger$ (a_k) is the creation (annihilation) operator of the k-mode SP, ω_k is the frequency of the incident k-mode SP, and σ_{e_j,e_j} $(\sigma_{e_j,g_j})=|e_j\rangle\langle e_j|(|e_j\rangle\langle g_j|)$ is the diagonal (off-diagonal) element of the QD operator with $|e_j\rangle$ $(|g_j\rangle)$ meaning the j-th QD in its excited (ground) state. Here, $g_j=(2\pi/\hbar\omega_k V)^{1/2}\Omega_j\mathbf{D_j}\cdot\hat{p}_k$ describes the coupling strength between SPs and the j-th QD, where $\mathbf{D_j}$ is the dipole moment of the j-th QD, V is the quantization volume, and $\hat{p}_k$ is the polarization vector of the SPs.

The stationary state of this combined QD plasmon system can be written as [12,22]:

$$
\begin{aligned}
|E_k\rangle = {} & \int \mathrm{d}z[\phi_{k,R}^\dagger(z)C_R^\dagger(z)+\phi_{k,L}^\dagger(z)C_L^\dagger(z)]|g_1,g_2\rangle|0\rangle_{\mathrm{sp}} \\
& + \sum_{j=1,2} e_{k_j}\sigma_{e_j,g_j}|g_1,g_2\rangle|0\rangle_{\mathrm{sp}}, \qquad (4)
\end{aligned}
$$

where $|g_1,g_2\rangle|0\rangle_{\mathrm{sp}}$ describes that both QDs are in the ground state with zero SP and e_{k_j} is the probability amplitude that the j-th QD absorbs the SP and jumps to its excited state. For a SP incident from the left, $\phi_{k,R}^\dagger(z)\equiv e^{ik_zz}[\theta(-z)+\alpha\theta(z)\theta(d-z)+t\theta(z-d)]$ and $\phi_{k,L}^\dagger(z)\equiv e^{-ik_zz}[r\theta(-z)+\beta\theta(z)\theta(d-z)]$. Here, t and r are the transmission and reflection amplitude, respectively, α and β are the probability amplitudes of the SP between $z=0$ and d, and $\theta(z)$ is the unit step function. The Hamiltonian [Eq. (3)] can be further transformed into real-space representation, $\tilde{H}$, and applied to the stationary state [Eq. (4)]. The transmission spectrum can then be obtained by solving the eigenvalue equation $\tilde{H}|E_k\rangle=E_k|E_k\rangle$. Figure 3(a) shows the transmission spectra for different magnitudes ($0\sim1.5T$) of the applied magnetic field. Here, we set the exciton energies of the QDs, $\hbar\Omega_1$ and $\hbar\Omega_2$, to be equal to the minima of the dispersion relations, $\omega_{\min}$, for $H_0=0$ and 1.5 T, respectively. The ratio of the coupling strength g_1/g_2 is set to be 10. As shown in Fig. 3(a), in the absence of the applied magnetic field, the transmission spectrum presents symmetric double peaks and the separation between these two peaks is reduced when increasing the magnitude of the magnetic

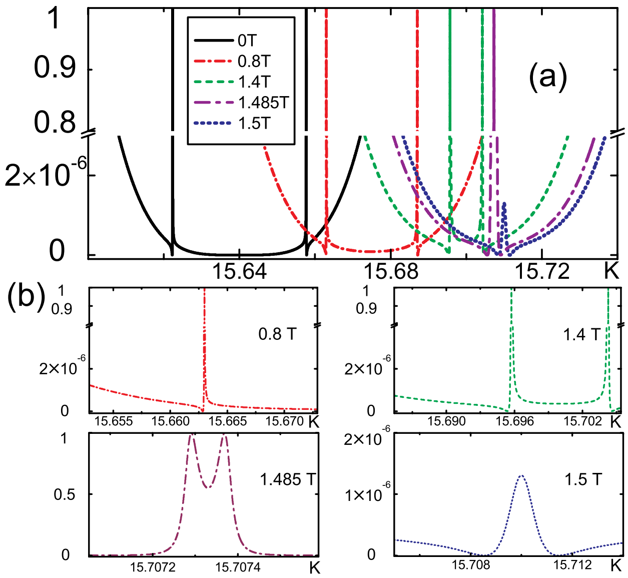

Fig. 3. (Color online) (a) Transmission spectra for the magnetic field $H_0 = 0$ (black-solid), 0.8 (red-short-dash-dotted), 1.4 (green-dashed), 1.485 (purple-dash-dotted), and 1.5 (blue-dotted) T. (b) The enlargement of the Fano lineshape in the transmission spectrum for the corresponding magnitudes of the magnetic field. The interdot distance d is assumed to be much smaller than the wavelength λ of the SP.

field. This is because, when $H_0 < 1.5T$, $\omega_{\min}$ is between Ω_1, and Ω_2 ($\Omega_1 < \omega_{\min} < \Omega_2$), there exists the interference between the localized and delocalized channels of the incident SP [20]. This interference also results in the Fano lineshapes around the two peaks. For $H_0 \geq 1.5T$, Ω_1 and Ω_2 are both smaller than $\omega_{\min}$, such that the interference is suppressed and the Fano lineshape is smeared out as shown in Fig. 3(b).

The Fano lineshapes appearing in Fig. 3(b) are small. This is because for $H_0 = 0 \sim 1.5T$, the ratio of the cyclotron frequency to the saturated plasma frequency $(= 3.76/\sqrt{2}\,\text{eV})$ is in the order of $10^{-6} \sim 10^{-5}$. In practice, these small lineshapes are not easy to be observed due to the imperfections of the material or other dissipations. However, since the disappearing process of the Fano lineshapes accompanies the reducing separation between the symmetric double peaks as shown in Fig. 3(b), observing the decrease of the interpeak separation can indirectly show the disappearance of the Fano resonance, even in the presence of the imperfections or dissipations.

In summary, we have studied the effect of the magnetic field on the system consisting of two QDs coupled to the nanowire SPs. In the presence of the magnetic field, the dispersion relations of SPs are upwardly displaced. Furthermore, we have also studied the transport properties of the incident SP and found that by appropriately choosing the exciton energies of the two QDs, the interference between the localized and delocalized channels of the incident SP can occur. This results in the symmetric double peaks and the Fano lineshape in the transmission spectrum. The double peaks would gradually combine together and the Fano lineshape will be smeared out in the presence of the applied magnetic field. In other words, this brings a possible way to control the scattering of the SP through varying the magnitude of the applied magnetic field.

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