Switching and Fano resonance via exciton–plasmon interaction*

Li Jian-Bo(李建波)†, He Meng-Dong(贺梦冬), Wang Xin-Jun(王新军),
Peng Xiao-Fang(彭小芳), and Chen Li-Qun(陈丽群)

Institute of Mathematics and Physics, Central South University of Forestry and Technology, Changsha 410004, *China*

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We further study theoretically the properties of switching and Fano resonance in a hybrid nanosystem consisting of two quantum dots (QDs) and a metal nanowire via exciton–plasmon interaction. The transmission of the single plasmon can be switched on or off in a wide-frequency region by adjusting the transition frequencies of the QDs and the phase of the propagating plasmon. Specifically, the dynamical mechanism of Fano-type transmission is further revealed and analyzed in detail.

Keywords: surface plasmon, quantum dots, quantum computation, optical waveguides and couplers

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1. Introduction

The interaction between excitons of semiconductor quantum dots (SQDs) and surface plasmons (SPs) of metal nanostructures is a research topic of growing interest.[1–14] These hybrid nanosystems via exciton–plasmon interaction exhibit many interesting and significant phenomena, such as surface plasmon amplification by stimulated emission of radiation,[1,2] single optical plasmon generation,[3] exciton–plasmon–photon conversion,[4] and plasmon-induced fluorescence enhancement,[5,6] energy transfer,[7,8] nonlinear Fano effect,[9] optical bistability,[10,11] etc. Based on exciton–plasmon interaction, a metal–semiconductor hybrid nanosystem can be explored for use in a quantum switch,[15,16] single-photon transistor,[17] nanosensor,[18] modulator,[19] etc.

The transport of a single plasmon can be adjusted through exciton–plasmon interaction. Recently, great attention has been focused on coherent single SP transport in metal nanowires (MWNs) coupling to QDs.[20–27] In these systems, the transmission spectrum with asymmetric Fano-type and switching a single plasmon on or off in a sharp frequency region have been reported.[16,24–27] However, switching a single propagating plasmon on or off in a wide frequency region and the dynamical evolution of symmetric Fano-type transmission have never been studied systematically.

In this paper, we further study theoretically the properties of switching and Fano resonance in a hybrid nanosystem consisting of two quantum dots (QDs) and a metal nanowire via exciton–plasmon interaction. We reveal and analyze in detail the switching property of a single plasmon in a wide-frequency region and the dynamical mechanism of Fano-type transmission.

2. Model and formalism

The schematic diagram of a hybrid nanosystem with a single metal nanowire and two SQDs is shown in Fig. 1. The metal nanowire is used as a one-dimensional (1D) SP waveguide, and the QDs act as two tunable mirrors. So a Fabry–Perot (FP) nanocavity will be formed between two QDs.

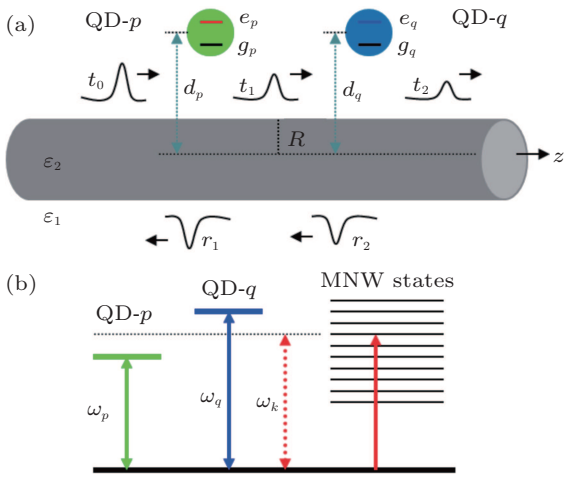


Fig. 1. (color online) Schematic diagram (a) and energy level diagram (b) of the hybrid system consisting of two quantum dots coupled to a metal nanowire. t_1 and t_2 (r_1, r_2) are the transmission (reflection) amplitudes of the plasmon interacting with QD-p and QD-q, respectively.

In the real space, the Hamiltonian of the system can be rewritten as[28] ($\hbar = 1$)

$$\begin{aligned} H = & \sum_{j=p,q} [(\omega_e^{(j)} - \mathrm{i}\Gamma'/2)\sigma_{ee}^{(j)} + \omega_g^{(j)}\sigma_{gg}^{(j)}] \\ & + \mathrm{i}v_g \int_{-\infty}^{\infty} \mathrm{d}z \left[a_{\mathrm{L}}^{\dagger}(z_j)\frac{\partial}{\partial z}a_{\mathrm{L}}(z_j) - a_{\mathrm{R}}^{\dagger}(z_j)\frac{\partial}{\partial z}a_{\mathrm{R}}(z_j) \right] \\ & + \sum_{j=p,q} g_i[(a_{\mathrm{R}}^{\dagger}(z_j) + a_{\mathrm{L}}^{\dagger}(z_j))\sigma_{ge}^{(j)} \\ & + (a_{\mathrm{R}}(z_j) + a_{\mathrm{L}}(z_j))\sigma_{ge}^{(j)}], \end{aligned} \tag{1}$$

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†Corresponding author. E-mail: jbli_opt@126.com

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where $\omega_e^{(j)}$ and $\omega_g^{(j)}$ are the eigenfrequencies of the ground state $|g\rangle$ and the excited state $|e\rangle$ of the QD-j, respectively; ω_k is the frequency of the incident k-mode SP, v_g is the group velocity of the SPs, $\omega_k = v_g|k|$; $\sigma_{ge}^j = |g\rangle_j\langle e|$ ($\sigma_{eg}^j = |e\rangle_j\langle g|$) is the lowering (raising) operator of the QD-j ($j = p, q$); $\sigma_{ee}^j = |e\rangle_j\langle e|$, $\sigma_{gg}^j = |g\rangle_j\langle g|$. $a_{\rm R}^\dagger(z_j)$ [$a_{\rm L}^\dagger(z_j)$] is the bosonic operator creating a right-going (left-going) plasmon at position z_j; $a_{\rm R}(z_j)$ [$a_{\rm L}(z_j)$] is the bosonic operator annihilating a right-going (left-going) plasmon at position z_j; Γ_{pl} and Γ' denote the decay rate into the SPs and the other channels, respectively.[29,30] An effective Purcell factor is expressed as $P = \Gamma_{pl}/\Gamma' = \Gamma_{pl}/(\Gamma_{\rm rad}+\Gamma_{\rm non-rad})$, where $\Gamma' = \Gamma_{\rm rad}+\Gamma_{\rm non-rad}$, with $\Gamma_{\rm rad}$ and $\Gamma_{\rm non-rad}$ being the emission into free space and nonradiative emission via ohmic loss with respective rates[29–31]

$$P = \left|1+\frac{\varepsilon_2-\varepsilon_1}{\varepsilon_2+\varepsilon_1}\frac{R^2}{d_j^2}\right|^2 \Bigg/ \left[\frac{3}{16k_0^2(d_j-R)^3\varepsilon_1^{3/2}}\mathrm{Im}\left(\frac{\varepsilon_2-\varepsilon_1}{\varepsilon_2+\varepsilon_1}\right) + \alpha_{pl}\cdot\frac{\mathrm{K}_1^2(Cd_j/R)}{(k_0R)^3}\right].$$

Here, ε_1 and ε_2 denote the dielectric permittivities in the regions outside and inside the metal nanowire, respectively; R is the radius of the Ag nanowire; d_j is the separation between QD$-j$ and the axis of nanowire; α_{pl} is a parameter depending on ε_1 and ε_2; k_0 is the vacuum wave vector; C is a constant; K_1 is one-order modified Bessel function; g_j describes the coupling strength between the QD-j and the SPs.[16,24]

The stationary state of the hybrid system is given by[28,32]

$$|\psi_k\rangle = \int \mathrm{d}z[\phi_{k,\rm R}^+(z)a_{\rm R}^+(z)+\phi_{k,\rm L}^+(z)a_{\rm L}^+(z)]\,|0,g\rangle + \sum_{j=1}^{2} e_k^{(j)}\,|0,e_j\rangle, \tag{2}$$

where $|0,g\rangle$ describes the two QDs that are both in ground state with zero plasmon; $|0,e_j\rangle$ denotes the QD-j in the excited state with zero plasmon; $e_k^{(j)}$ is the probability amplitude of the QD-j in the excited state; $\phi_{k,\rm R}^+(z)$ and $\phi_{k,\rm L}^+(z)$ are the mode functions defined by $\varphi_{k,\rm R}^+(z<0) = \mathrm{e}^{\mathrm{i}kz}$, $\varphi_{k,\rm R}^+(0<z<L) = t_1\,\mathrm{e}^{\mathrm{i}k(z-L)}$, $\varphi_{k,\rm R}^+(z>L) = t_1\,\mathrm{e}^{\mathrm{i}k(z-2L)}$, $\varphi_{k,\rm L}^+(z<0) = r_1\,\mathrm{e}^{-\mathrm{i}kz}$, $\varphi_{k,\rm L}^+(0<z<L) = r_2\,\mathrm{e}^{-\mathrm{i}k(z-L)}$, $\varphi_{k,\rm L}^+(z>L) = 0$,[28,33] L is the distance between two QDs. By using the eigenvalue equation $H|\psi_k\rangle = E_k|\psi_k\rangle$ ($E_k = h\omega_k$), one can obtain

$$-\mathrm{i}v_g\frac{\partial}{\partial z}\phi_{k,\rm R}^+(z_j)+g_je_k^{(j)} = \omega_k\phi_{k,\rm R}^+(z_j), \tag{3}$$

$$\mathrm{i}v_g\frac{\partial}{\partial z}\phi_{k,\rm L}^+(z_j)+g_je_k^{(j)} = \omega_k\phi_{k,\rm L}^+(z_j), \tag{4}$$

$$(\omega_{eg}^{(j)}-\mathrm{i}\Gamma'/2)e_k^{(j)}+g_j[\phi_{k,\rm R}^+(z_j)+\phi_{k,\rm L}^+(z_j)] = \omega_ke_k^{(j)}. \tag{5}$$

Substituting the mode functions $\phi_{k,\rm R}^+(z)$ and $\phi_{k,\rm L}^+(z)$ into Eqs. (3)–(5) yields

$$t_1 = \frac{\mathrm{e}^{\mathrm{i}kl}[2(\Gamma'/\Omega+2\mathrm{i}\delta_p/\Omega)+(\Gamma'/\Omega+2\mathrm{i}\delta_p/\Omega)(\Gamma'/\Omega+2\mathrm{i}\delta_q/\Omega)]}{4(1-\mathrm{e}^{2\mathrm{i}kl})+4(\Gamma'/\Omega+\mathrm{i}(\delta_p+\delta_q)/\Omega)+(\Gamma'/\Omega+2\mathrm{i}\delta_p/\Omega)(\Gamma'/\Omega+2\mathrm{i}\delta_q/\Omega)}, \tag{6}$$

$$t_2 = \frac{\mathrm{e}^{2\mathrm{i}kl}(\Gamma'/\Omega+2\mathrm{i}\delta_q/\Omega)(\Gamma'/\Omega+2\mathrm{i}\delta_p/\Omega)}{4(1-\mathrm{e}^{2\mathrm{i}kl})+4(\Gamma'/\Omega+\mathrm{i}(\delta_p+\delta_q)/\Omega)+(\Gamma'/\Omega+2\mathrm{i}\delta_p/\Omega)(\Gamma'/\Omega+2\mathrm{i}\delta_q/\Omega)}, \tag{7}$$

$$r_1 = \frac{2[2(-1+\mathrm{e}^{2\mathrm{i}kl})-(1+\mathrm{e}^{2\mathrm{i}kl})\Gamma'/\Omega+2\mathrm{i}(\delta_p/\Omega\,\mathrm{e}^{2\mathrm{i}kl}+\delta_q/\Omega)]}{4(1-\mathrm{e}^{2\mathrm{i}kl})+4(\Gamma'/\Omega+\mathrm{i}(\delta_p+\delta_q)/\Omega)+(\Gamma'/\Omega+2\mathrm{i}\delta_p/\Omega)(\Gamma'/\Omega+2\mathrm{i}\delta_q/\Omega)}, \tag{8}$$

$$r_2 = -\frac{2\mathrm{e}^{\mathrm{i}kl}(\Gamma'/\Omega+2\mathrm{i}\delta_p/\Omega)}{4(1-\mathrm{e}^{2\mathrm{i}kl})+4(\Gamma'/\Omega+\mathrm{i}(\delta_p+\delta_q)/\Omega)+(\Gamma'/\Omega+2\mathrm{i}\delta_p/\Omega)(\Gamma'/\Omega+2\mathrm{i}\delta_q/\Omega)}, \tag{9}$$

where $\omega_{eg}^{(j)} = \omega_e^{(j)}-\omega_g^{(j)}$, $\omega_{eg}^{(j)}-\omega_k = \delta_j$, $\Omega = g^2/v_g$, and $\Delta_j = \delta_j/\Omega$. We suppose $g = g_j$. The transmission probability and reflection probability of the plasmon are defined as $T_l = |t_l|^2$ and $R_l = |r_l|^2$ ($l = 1, 2$), respectively. Only R_1 and T_2 describe the transport properties of the surface plasmon, while T_1 and R_2 reflect the mode strength of the FP nanocavity. For simplicity, we only consider a limited case for Purcell factor $P\to\infty$ in the following discussion.

3. Results and discussion

The transmission probabilities T_2 each as a function of the detuning Δ for $\Delta_p = -\Delta_q = \Delta$ with various values of phase factor kL, are plotted in Fig. 2. As shown in Fig. 2, one can find that the full width at half maximum (FWHM) of the transmission spectrum increases from 0 to 4 as the phase factor kL increases from 0 to $\pi/2$. The transmission spectrum of $kL = \theta$ is the same as that of $kL = \pi-\theta$. Due to the spontaneous emission of the QDs, the plasmon will be completely reflected back by the two QDs at $\omega_k = \omega_{eg}^{(p)} = \omega_{eg}^{(q)}$, and the two QDs act as two perfect mirrors ($T_2 = 0$). The transmission probabilities T_2 are always equal to 1 when $kL = 0, \pi$. As is well known, a quantum switch has two states (on and off) for controlling the transmission of a single plasmon.[16] The switch is off for $T_2 = 0$, and on for $T_2 = 1$. In our calculations, the switch is always off when the plasmon is in the resonance condition ($\omega_k = \omega_{eg}^{(p)} = \omega_{eg}^{(q)}$), while the switch is always on for $\Delta_p = -\Delta_q = \Delta$ when $kL = 0, \pi$. These results will provide a

new idea for designing a filter or a switch.

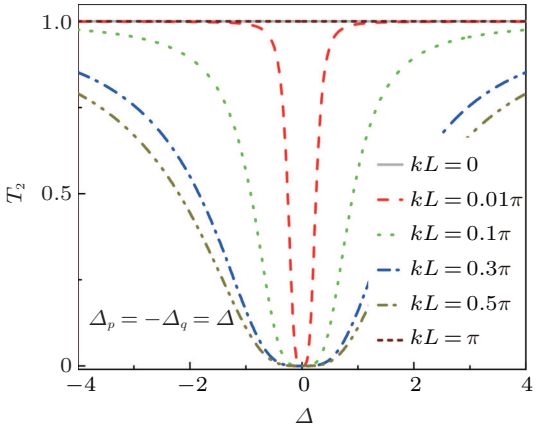


Fig. 2. (color online) Transmission spectra of a single plasmon for $\Delta_p = -\Delta_q$ for the phase factor $kL = 0$, π, 0.01π, 0.1π, 0.3π, 0.5π, and π.

In order to further explore the switch characteristics of the propagating plasmon, figures 3(a) and 3(b) exhibit the transmission probabilities T_2 each as a function of the detuning Δ for $\Delta_p = \Delta_q = \Delta$ with various values of kL. When $0 < kL < \pi/2$, the transmission spectra have a set of distinct Fano-type line shapes, and T_2 reaches its maximum value 1 at $\Delta = 0.325$, 0.727, 1.38 for $kL = 0.1\pi$, 0.2π, 0.3π, respectively. The transmission peak shifts from left to right and the peak becomes smoother as kL increases. When $\pi/2 < kL < \pi$, T_2 is equal to 1 at $\Delta = -0.325$, -0.727, -1.38 for $kL = 0.9\pi$, 0.8π, 0.7π, respectively. The transmission peak shifts from right to left as kL increases. This asymmetric Fano-type transmission is useful for designing biosensors.[34] From Figs. 3(a) and 3(b), one can see that the Fano-type transmission spectrum for $kL = \theta$ is symmetric with respect to that of $kL = \pi - \theta$. Moreover, one can obtain the conditions where the plasmon switch is on ($T_2 = 1$) are $\Delta_p = \tan(2kL)$ and $\sin(2kL) - \cos(2kL)\Delta_p - \Delta_q = 0$ derived from Eq. (8). As long as the frequency detunings Δ_p and Δ_q match well with the phase factor kL, the switch can be switched on ($T_2 = 1$) or off ($T_2 = 0$). The positions of transmission peak (δ_0/Ω) as a function of kL are plotted in Fig. 3(c).

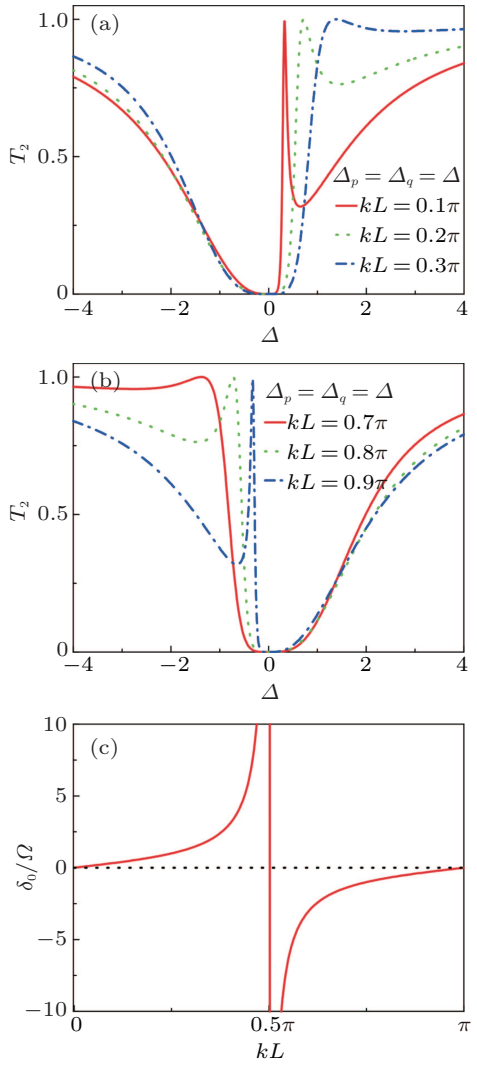


Fig. 3. (color online) Transmission probabilities T_2 each as a function of detuning Δ for $\Delta_p = \Delta_q$ when $kL = 0.1\pi$, 0.2π, 0.3π (a), 0.7π, 0.8π, and 0.9π (b). The position of transmission peak (δ_0/Ω) as a function of kL (c).

Figure 4(a) show the transmission probabilities T_2 each as a function of kL for $\Delta_p = \Delta_q = \Delta$ when $\Delta = 0.1$, 0.5, and 1.0. One can obtain that the transmission probability $T_2 = 1$ always happens at $kL = n\pi + \arctan(\Delta)$ ($n = 0, 1, 2, \ldots$), and the period of T_2 keeps invariant. Moreover, the peak position has an obviously different shift for a different detuning Δ. As

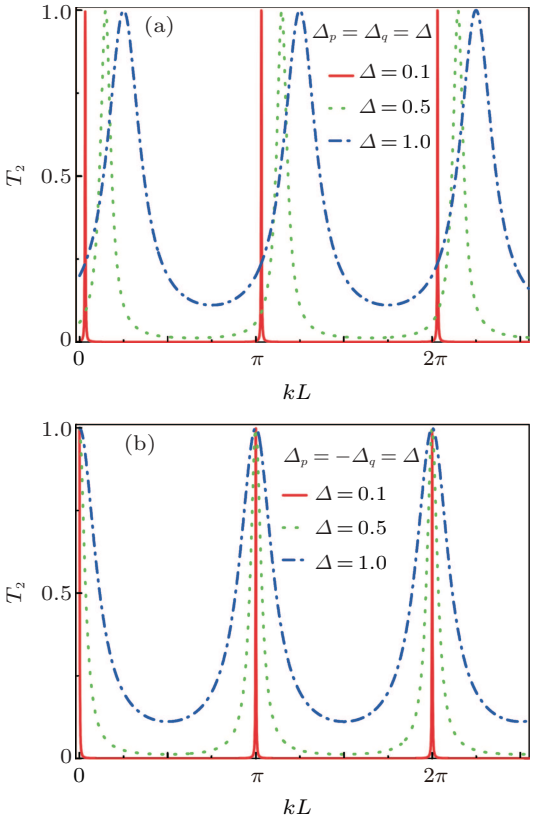


Fig. 4. (color online) Transmission probabilities T_2 each as a function of phase factor kL with detuning $\Delta = 0.1$, 0.5, and 1.0 when $\Delta_p = \Delta_q$ (a) and $\Delta_p = -\Delta_q$ (b).

a comparison, figure 4(b) shows that the position of the transmission peak keeps invariant for $\Delta_p = -\Delta_q = \Delta$ and $T_2 = 1$ always happens at $kL = n\pi$ in spite of various values of Δ. According to the periodicity of the transmission spectrum, it is clear that the switch can be switched on and off periodically by adjusting the frequency detunings Δ_p and Δ_q.

The transmission probabilities T_2 each as a function of detuning Δ_q for $\Delta_p = 1$ with different values of phase factor kL are exhibited in Fig. 5. When $kL = \pi/8$, the transmission spectrum is a symmetrical curve with Lorentz line shape. When kL increases to $\pi/6$ or $\pi/4$, an asymmetrical Fano-type transmission spectrum can be obtained. The dynamical evolutions of Fano-type transmission spectra are plotted clearly in Fig. 5. Therefore, the formation and evolution of the Fano-type transmission spectrum may be attributed to the interaction between Fabry–Perot nanocavity and the plasmon.

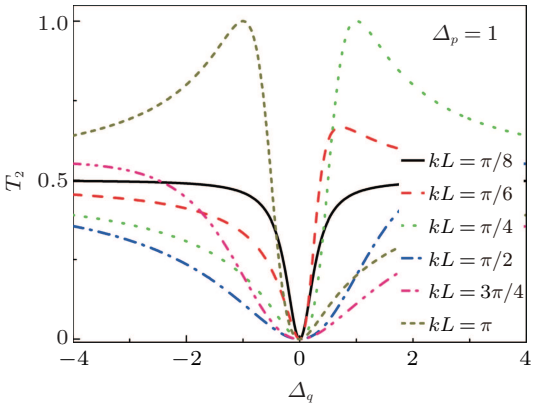


Fig. 5. (color online) Transmission probabilities T_2 each as a function of detuning Δ_q for $\Delta_p = 1$ when $kL = \pi/8$, $\pi/6$, $\pi/4$, $\pi/2$, $3\pi/4$, and π.

Figure 6 shows the transmission probabilities T_2 each as a function of detuning Δ_q for $kL = \pi$ with different values of Δ_p. As shown in Fig. 6, the transmission probability T_2 is equal to 0 when $\Delta_p = 0$ in spite of the value of Δ_q. When $\Delta_p = 0.1$, one can obtain a Fano-type transmission spectrum. The line shape of transmission spectrum attributed to Fano resonance will become more obvious as the detuning Δ_p further increases.

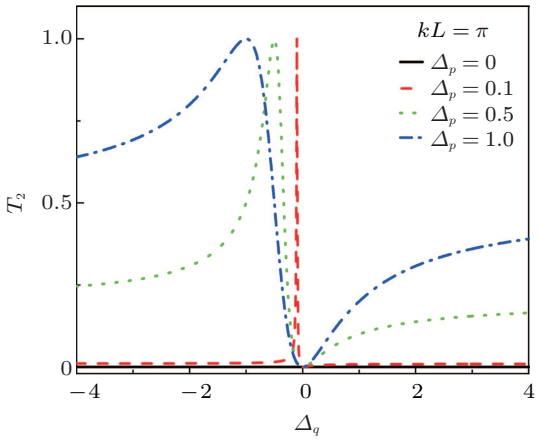


Fig. 6. (color online) Transmission probabilities T_2 each as a function of detuning Δ_q for $kL = \pi$ when $\Delta_p = 0$, 0.1, 0.5, and 1.0.

4. Conclusion

In this paper, the switching property and Fano resonance in a hybrid nanosystem composed of two quantum dots (QDs) and a metal nanowire via exciton–plasmon interaction are studied theoretically. We can switch the transport of a single plasmon on or off in a wide-frequency region, and further reveal and analyze in detail the dynamical mechanism of Fano-type transmission. Our results may be useful for nanoswitch, biosensors, and quantum information and quantum computation.

References

[1] Bergman D J and Stockman M I 2003 *Phys. Rev. Lett.* **90** 027402
[2] Oulton R F, Sorger V J, Zentgraf T, Ma R M, Gladden C, Dai L, Bartal G and Zhang X 2009 *Nature* **461** 629
[3] Akimov A V, Mukherjee A, Yu C L, Chang D E, Zibrov A S, Hemmer P R, Park H and Lukin M D 2007 *Nature* **450** 402
[4] Fedutik Y, Temnov V V, Schops O, Woggon U and Artemyev M V 2007 *Phys. Rev. Lett.* **99** 136802
[5] Sadeghi S M, West R G and Nejat A 2011 *Nanotechnology* **22** 405202
[6] Gu Y, Huang L, Martin O J F and Gong Q H 2010 *Phys. Rev. B* **81** 193103
[7] Govorov A O, Lee J and Kotov N A 2007 *Phys. Rev. B* **76** 125308
[8] Zhou Z K, Li M, Yang Z J, Peng X N, Su X R, Zhang Z S, Li J B, Kim N C, Yu X F, Zhou L, Hao Z H and Wang Q Q 2010 *ACS Nano* **4** 5003
[9] Govorov A O, Bryant G W, Zhang W, Skeini T, Lee J, Kotov N A, Slocik J M and Naik R R 2006 *Nano Lett.* **6** 984
[10] Malyshev A V and Malyshev V A 2011 *Phys. Rev. B* **84** 035314
[11] Li J B, Kim N C, Cheng M T, Zhou L, Hao Z H and Wang Q Q 2012 *Opt. Express* **20** 1856
[12] Sadeghi S M, Deng L, Li X and Huang W P 2009 *Nanotechnology* **20** 365401
[13] Xiao Z H, Zheng L and Lin H Z 2012 *Opt. Express* **20** 1219
[14] Liu S D, Cheng M T, Yang Z J and Wang Q Q 2008 *Opt. Lett.* **33** 851
[15] Sadeghi S M 2010 *Nanotechnology* **21** 355501
[16] Kim N C, Li J B, Yang Z J, Hao Z H and Wang Q Q 2010 *Appl. Phys. Lett.* **97** 061110
[17] Chang D E, Sørensen A S, Demler E A and Lukin M D 2007 *Nat. Phys.* **3** 807
[18] Hatef A, Sadeghi S M, Boulais É and Meunier M 2013 *Nanotechnology* **24** 015502
[19] Pacifici D, Lezec H J and Atwater H A 2007 *Nat. Photon.* **1** 402
[20] Cheng M T, Luo Y Q, Wang P Z and Zhao G X 2010 *Appl. Phys. Lett.* **97** 191903
[21] Cheng M T 2011 *Acta Phys. Sin.* **60** 117301 (in Chinese)
[22] Cheng M T 2012 *Opt. Commun.* **285** 804
[23] Chen G Y, Lambert N, Chou C H, Chen Y N and Nori F 2011 *Phys. Rev. B* **84** 045310
[24] Chen W, Chen G Y and Chen Y N 2010 *Opt. Express* **18** 10360
[25] Chen W, Chen G Y and Chen Y N 2011 *Opt. Lett.* **36** 3602
[26] Chen G Y and Chen Y N 2012 *Opt. Lett.* **37** 4023
[27] Cheng M T and Song Y Y 2012 *Opt. Lett.* **37** 978
[28] Shen J T and Fan S 2005 *Opt. Lett.* **30** 2001
[29] Chang D E, Sørensen A S, Hemmer P R and Lukin M D 2006 *Phys. Rev. Lett.* **97** 053002
[30] Chang D E, Sørensen A S, Hemmer P R and Lukin M D 2007 *Phys. Rev. B* **76** 035420
[31] Li J B, Cheng M T, Yang Z J and Hao Z H 2009 *Chin. Phys. Lett.* **26** 113202
[32] Tsoi T S and Law C K 2008 *Phys. Rev. A* **78** 063832
[33] Gu L M 2012 *Chin. Phys. Lett.* **29** 104206
[34] Xiao X F, Li M, Liu Y C, Li Y, Sun X and Gong Q 2010 *Phys. Rev. A* **82** 065804