Optics Communications 419 (2018) 25–29

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Transport properties of surface plasmons in a nonlinear nanowire coupled to quantum dots with azimuthal angle differences

Jin-Song Huang [a,b,*], Jia-Hao Zhang [a], Yan Wang [c], Zhong-Hui Xu [a], You-Wen Huang [a]

[a] School of Information Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China
[b] Department of Physics, South China University of Technology, Guangzhou 510640, China
[c] School of Foreign Studies, Jiangxi University of Science and Technology, Ganzhou 341000, China

ARTICLE INFO

Keywords:
Quantum transport
Surface plasmons
Quantum dots
Azimuthal angles

ABSTRACT

We investigate single surface-plasmon transport in a nonlinear nanowire strongly coupled to multiple quantum dots with azimuthal angle differences. Exact expressions for the scattering coefficients are obtained by adopting the real-space Hamiltonian and the transfer matrix approach. Fano-like resonance and jiggling behavior in the scattering spectra are exhibited, and a plasmonic switch can be achieved, by adjusting azimuthal angle differences of quantum dots. The periodic transmission and reflection profile is also revealed at specific azimuthal angles. These results show that the azimuthal angle may be utilized as a new handle to control the surface plasmon transport.

1. Introduction

In recent years coherent single-photon transport in one-dimensional waveguide has been widely investigated due to its potential applications in quantum computation and quantum information processing [1–8]. Surface plasmons(SPs), known as propagating excitations of electrons along the metal–dielectric interface [9], play important roles in confining electromagnetic wave at the subwavelength optical scale to realize functional nanophotonic devices [10]. As a strong analogy to light propagation in common dielectric optical components [11–13], SPs have attracted extensive attention in the nanophotonic field.

With the current experimental efforts, an integrated system with a metal nanowire coupled to a single quantum dot(QD) has been fabricated successfully and demonstrated as a plasmonic waveguide [14,15], which provides a powerful platform for the study of the coherent nanowire SP transport. Moreover, deterministic loading and submicrometer positioning of single QDs in a nanowire has been achieved [16], which leads to the possibilities of investigating SP scattering by multiple separate QDs. Recently, in the coupled system with linear dispersion relations of the waveguide mode, a lot of theoretical investigations have been devoted to the SP transport related to switchings [17,18], transistors [19,20], Fano resonance [21], scattering grating [22], and generating entangled states [23–25], etc. Further, in the nonlinear dispersion regime of metal nanowire SPs, many interesting physical behaviors, including the four-peaks reflection [26], jiggling scattering, and Fano-like resonance [27–29], have also been exhibited. For example, in such a nonlinear plasmonic waveguide, Chen et al. [27] investigated the generations of the spectral jiggling behavior and the Fano-like line shape due to the quantum interference between the localized and delocalized channels, by adjusting the distance of two QDs. Interesting, a recent study by Kuo et al. [30] shows that, besides the separation of two QDs near a cylindrical metal nanowire, the azimuthal angle difference between QDs can also be considered as an available parameter. By focusing on the azimuthal angle variable in a nanowire with the linear dispersion relation, novel features in the scattering spectra such as periodic maximum transmission (minimum reflection) is revealed [30].

Motivated by the above considerations, we investigate the scattering properties of the SPs in a nonlinear plasmonic waveguide, where the nanowire SPs are coupled to multiple QDs with an azimuthal angle difference. By adopting the real-space Hamiltonian and the transfer matrix approach, the scattering spectra of the SPs are obtained exactly, and three cases with different QDs are discussed in detail. In the single-dot case, double-peak structure in the transmission spectrum for the negative detuning is found due to the nonlinear dispersion relation. In contrast to previous scheme [27] concentrating on adjusting the separation of two QDs, Fano-like resonance in the scattering spectra is also exhibited by varying azimuthal angle difference of two QDs in the double-QD case, since the azimuthal angle also yields the phase difference between two QDs, which is similar to the phase difference related to

* Corresponding author at: School of Information Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China.
E-mail address: jshuangjs@126.com (J.-S. Huang).

https://doi.org/10.1016/j.optcom.2018.03.010
Received 1 December 2017; Received in revised form 3 March 2018; Accepted 5 March 2018

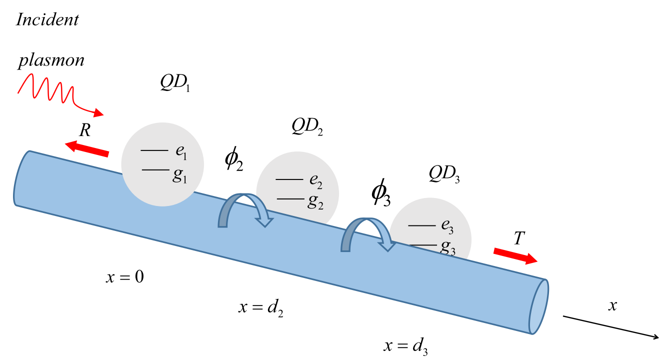

Fig. 1. (Color online) Schematic diagram for scattering of single SPs by three QDs coupled to the cylindrical metal nanowire. Three QDs characterized by $|g_n\rangle$ and $|e_n\rangle(n = 1, 2, 3)$ are located at $x = d_1(d_1 = 0)$, $x = d_2$ and $x = d_3$, with an azimuthal angle $\phi_1 = 0$, ϕ_2 and ϕ_3, respectively. An incoming wave from the left of the nanowire is reflected and transmitted with the coefficients R and T, respectively.

the separation. Moreover, a plasmonic switch could be achieved for the strong SP-QD coupling at specific azimuthal angles. Furthermore, the periodic scattering profile for different azimuthal angles is revealed in the three-dot case. The possible generalization to the N-QD ($N > 3$) case is easy to implement by using the transfer matrices. These results show that the azimuthal angles emerge as a new handle to the scattering of the SPs in a nonlinear nanowire, which may offer a novel way to control the surface plasmon transport.

2. Theoretical model

As shown in Fig. 1, the considered system consists of three two-level QDs coupled to a cylindrical metal nanowire. QD-1 (2,3) is characterized by the ground state $|g_{1(2,3)}\rangle$ and excited state $|e_{1(2,3)}\rangle$. For simplicity, we assume that these three QDs are identical with equal energy spacing $\hbar\omega_0$, and have the same separation from the metal wire, which indicates that their couplings to the nanowire SPs are the same. These three QDs are separated respectively with the distances $d_1(d_1 = 0)$, d_2, and d_3, and with the angles $\phi_1(\phi_1 = 0)$, ϕ_2 and ϕ_3, where d_n is the distance between QD-1 and QD-n along the $\hat{x}$ direction of the metal nanowire, and ϕ_n is the angle of nth QD with reference to QD-1 along the $\hat{\varphi}$ direction. As the right-moving modes propagate along the $\hat{x}$ and $\hat{\varphi}$ directions, the phase differences between two QDs are provided by $ikx + im\varphi$ [30], where k and m are the wavenumber of the incident SP and quantum number governing the x and φ components, respectively. Note that the phase differences are governed by the separation and the azimuthal angle difference between QDs, as an available parameter, the azimuthal angle plays an essential role similar to the separation for the transport of SPs.

For the dispersion relations of nanowire SPs, we here focus on the nonlinear case with 1th excitation mode. In a cylindrical silver nanowire with the QD-nanowire separation of 10.76 nm, a parabolic dispersion curve with a local minimum is exhibited [31,32]. The dispersion ω_k around the local minimum can be approximated as a quadratic form: $\omega_k = \omega_l + A(k - k_0)^2$, where k_0 is the wavevector for the local minimum frequency ω_l. Adopting the units in Refs. [27,33], the value of A is around 0.0001, and the reduced wavevector $K_0(= k_0c/\omega_p)$ around the local minimum is about 15, where $\hbar\omega_p = 3.76$ eV is the plasma energy of the silver nanowire, and $\lambda_0 = 2\pi/k_0 = 21.9$ nm. Here the colloidal CdSe/ZnS QD can be employed since its transition energy from the ground state to the excited state is around 2–2.5 eV, which is compatible with the corresponding saturation plasma energy (≈2.66 eV) of the silver nanowire with plasmon energy $\hbar\omega_p = 3.76$ eV [23,32].

The real-space Hamiltonian describing the system can be written as

$$\begin{aligned} H/\hbar = & \iint dx d\varphi \Big\{ (\omega_l + Ak_0^2)[C_R^\dagger(x,\varphi)C_R(x,\varphi) + C_L^\dagger(x,\varphi)C_L(x,\varphi)] \\ & - 2Ak_0[-iC_R^\dagger(x,\varphi)\frac{\partial}{\partial x}C_R(x,\varphi) + iC_L^\dagger(x,\varphi)\frac{\partial}{\partial x}C_L(x,\varphi)] \\ & + A[\frac{\partial}{\partial x}C_R^\dagger(x,\varphi)\frac{\partial}{\partial x}C_R(x,\varphi) + \frac{\partial}{\partial x}C_L^\dagger(x,\varphi)\frac{\partial}{\partial x}C_L(x,\varphi)] \\ & + \sum_{n=1,2,3} V\delta(x - d_n)\delta(\varphi - \phi_n)[C_R^\dagger(x,\varphi)|g_n\rangle\langle e_n| \\ & + C_L^\dagger(x,\varphi)|g_n\rangle\langle e_n| + H.c.] \Big\} + \sum_{n=1,2,3}(\omega_0 - i\frac{\Gamma}{2})|e_n\rangle\langle e_n|, \end{aligned} \tag{1}$$

where we have taken the energy level of the ground state $|g_n\rangle$ as the energy reference. $C_R^{(\dagger)}(x,\varphi)$ $[C_L^{(\dagger)}(x,\varphi)]$ denotes the creation operator of a right(left)-traveling surface plasmon in the nanowire at the position x and with the azimuthal angle φ. $\delta(x - d_n)[\delta(\varphi - \phi_n)]$ indicates that the interaction occurs at $x = d_n[\varphi = \phi_n]$. V describes the coupling strength between SPs and QDs. ω_0 denotes the transition frequency of excited state of the QDs. $|e_n\rangle\langle e_n|$ represents the diagonal element and $|g_n\rangle\langle e_n|$ represents the off-diagonal of the nth QD operator. $\Gamma = \gamma_0 + \Gamma_0$ is the total dissipation, which includes the exciton decay rate into free space γ_0 and the Ohmic loss Γ_0. Here the Ohmic loss of plasmons during the propagation is included since the loss of the plasmon is equivalent to the lose of the QD excitation [23].

3. Transport properties of single SPs

The transport properties of single SPs in the nanowire are characterized by the transmission coefficient T and reflection coefficient R. As a comparison, we investigate the transport properties in the single-QD, double-QD and triple-QD case in detail, respectively.

3.1. Transport properties in the single-QD case

We first discuss the scattering by the single QD in the nanowire. The real-space Hamiltonian of the single-QD system is reduced by taking $n = 1$ in the Eq. (1). Assume that the QD is initially in its ground state $|g_1\rangle$ and a single SP is incident from the left of the nanowire with the energy $E_k = \hbar\omega_k$. The scattering eigenstate of the Hamiltonian is give by

$$|\psi_1\rangle = \int dx[\phi_R(x)C_R^\dagger(x) + \phi_L(x)C_L^\dagger(x)]|\emptyset, g_1\rangle + \xi|\emptyset, e_1\rangle, \tag{2}$$

where $\phi_{R/L}$ is the single-SP wave function in the right/left of the nanowire. $|\emptyset, g_1\rangle$ denotes that QD-1 is in the ground state with no SPs, and ξ is the excitation amplitude of the QD state. Furthermore, the corresponding wave function can be expressed as

$$\begin{aligned} \phi_R(x) &= t_1 e^{ikx}\theta(x) + e^{ikx}\theta(-x), \\ \phi_L(x) &= r_1 e^{-ikx}\theta(-x), \end{aligned} \tag{3}$$

where t_1 and r_1 are the transmission and reflection amplitudes in the nanowire, respectively. $\theta(x)$ is the Heaviside step function with $\theta(0) = 1/2$.

By solving the eigen-equation $H|\psi_1\rangle = E_k|\psi_1\rangle$, the expressions of t_1 and r_1 can be obtained,

$$\begin{aligned} t_1 &= \frac{Ai(2k_0 - k)[A(k - k_0)^2 + \Delta + i\frac{\Gamma}{2}]}{Ai(2k_0 - k)[A(k - k_0)^2 + \Delta + i\frac{\Gamma}{2}] + V^2}, \\ r_1 &= -\frac{V^2}{Ai(2k_0 - k)[A(k - k_0)^2 + \Delta + i\frac{\Gamma}{2}] + V^2}, \end{aligned} \tag{4}$$

where $\Delta = \omega_l - \omega_0$ is the detuning between ω_l and the two-level energy spacing.

Eq. (4) indicates that two unities (zeros) in $R = |r_1|^2$ $(T = |t_1|^2)$ emerge for negative detuning, which corresponds to two peaks (dips) in