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Theoretical modelling of tunable narrow band reflective spectrum using nanoscale surface plasmons

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ABSTRACT

The spectrum width can be narrowed to a certain degree by decreasing the coupling strength for the two-level emitter coupled to the propagating surface plasmon. But the width can not be narrowed any further because of the loss of the photon out of the system by the spontaneous emission of the emitter. Here we accurately solve the single photon scattering problem for the surface plasmon coupling with a four-level tripod emitter, and propose a new scheme to obtain the reflective spectrum with tunable ultranarrow band. It is shown that the spectrum width can be narrowed avoiding the impact of the loss. Furthermore, the position of ultranarrow peak can be tunable by choosing the appropriate parameters.

1. Introduction

In recent years, the coupling between surface plasmon polaritons(SPPs) and optical emitters has attracted considerable attentions because of their wide application in many aspects [1–25]. The two-level emitter within the waveguide can act as a perfect mirror for the light field at resonance [6,17]. The Λ-type three-level emitter system(ΛLS) can realize electromagnetically induced transparency (EIT) mechanism to control behavior of the probe photon by applying a classical control light beam in the system [14,16]. Similarly, two separated two-level emitters system can also exhibit EIT-like transmission spectrum by adjusting the distance between the two emitters [10,12,19]. However, until now, the coupling properties in the four-level tripod emitter system(FLS) have not been investigated. As we all know, ultra-narrow spectrum has shown great potential in many different areas such as laser stabilization [26,27], high-resolution spectroscopy [28–31], and compressed optical energy [32]. In the two-level emitter coupling with SPPs systems(TLS), the linewidth of the reflection peak is proportional to V^2/v_g, where V is the coupling strength, and v_g is the group velocity of the photons and can be simplified as the velocity of the light [2]. So the reflection spectrum can be narrowed in the weak coupling regime [33]. However if the coupling strength is further decreased, the narrowed reflective spectrum shall be very weak because that most of the spontaneous emission of emitters is guided into the free space or non-radiative emission. In this letter, we shall propose a practical scheme to obtain tunable narrow band spectrum with great tunability and facility in the system of the optical emitter coupling the nanowire surface plasmons. It is shown that the reflective spectrum width can be narrowed avoiding the impact of the loss.

The paper is organized as follows. In Section 2, we shall revisit the problems of the photon transportation of TLS and discuss the effect of the loss on the linewidth narrowing. In section 3, we shall solve the reflective spectrum of FLS based on the theory of single-photon scattering, and propose a practical scheme to obtain tunable narrow band spectrum based on FLS. We shall also provide the comparison among the TLS, FLS with detuning field and FLS with resonant control field on the effect of linewidth narrowing. It is shown to be great tunability and facility for our proposal. And in Section 4, we shall conclude this paper. It should be pointed out that all the theoretical analyses in this paper are carried out by MATLAB codes.

2. The effect of loss on the linewidth narrowing in TLS

As shown in Fig. 1, our model consists of a single optical emitter placed on a metallic nanowire. The spontaneous emission of emitters can either emit into the guided surface plasmons of the nanowire with rate Γ or into all other possible channels with rate Γ' [2]. Here we define the ratio Γ/Γ' to quantify the coupling strength, and investigate the effect of the coupling strength on the linewidth narrowing. For simplicity, we fix the parameter Γ' and vary the parameter Γ to quantify the different coupling strength Γ/Γ'.

It is well known that for the photon absorption in the waveguide, losses are particularly strong in plasmonic systems. Here, we adopt the method proposed by the authors in the Ref. [2,34] as shown in Fig. 1. The surface plasmons are used to achieve the coupling with the emitter

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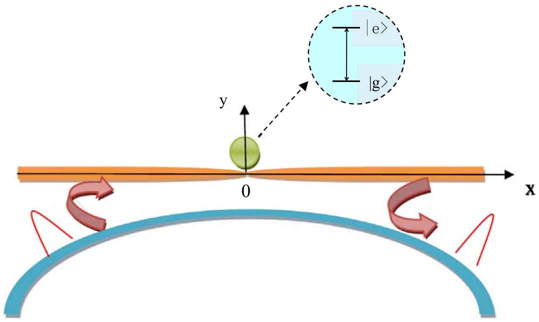

Fig. 1. Schematic diagram of a metal nanowire couple to a two level optical emitters. The surface plasmons are used to achieve the coupling with the emitter over a short distance, but are rapidly in- and out-coupled to conventional waveguides for long-distance transport.

over a short distance, but are rapidly in- and out-coupled to conventional waveguides for long-distance transport. It should be pointed out that some kinds of low loss plasmonic waveguide can be good candidates for the in- and out-coupled waveguides [35,36].

The scattering problem for a single photon in a one-dimensional waveguide coupled to a two-level quantum emitter has been solved exactly [2,16,33,37]. Here we just outline the results and put emphasis on the effect of the loss on the linewith narrowing in TLS. The reflection coefficient for a monochromatic input state with wave number k can be written as [16]:

$$r_k = -\frac{1}{1 + \Gamma'/\Gamma - 2i(\omega_1 - ck)/\Gamma} \tag{1}$$

where ω_1 is the level spacing between the excited state and the ground state, and the product ck is the energy of the incident photon. The corresponding reflection amplitude is given by

$$R \equiv |r_k|^2 \tag{2}$$

The changes of linewidth as a function of the ratio of $(\Delta - f_c)/\Gamma'$ is shown in Fig. 2, where $\Delta = (\omega_1 - ck)$, and f_c denotes the central frequency of the reflective spectrum. We can see that the maximum value of the reflective amplitude for TLS occurs with the emitter on resonance with the SPPs, therefore the reflective spectrum is demonstrated to be a single peak and the central frequency f_c is zero. At resonance and strong coupling, most of the energy of the plasmon is reflected. And with the decrease of the coupling strength, the linewidth of reflective spectrum is getting more and more narrow. But at the same time, the amplitude of reflective spectrum also decreases. This is because that the decreasing of the parameter means the declining of the spontaneous emission rate into the surface plasmons. In other word, more of the photon is injected into the free space by spontaneous emission or ohmic losses by the propagation waveguide, which are both irreversible processes for the whole system and consume the total energy of the system. Therefore, the reflective spectrum is decreasing with decreasing values of Γ in Fig. 2. Especially for the case of $\Gamma = 0.1$, the maximum of the spectrum is only about 0.25. Obviously the reflective spectrum is too faint. So a new scheme to obtain narrowed spectrum with enough intensity is needed.

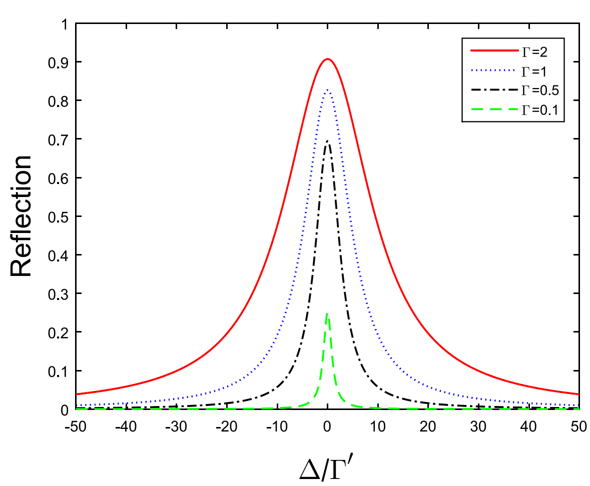

Fig. 2. The single-photon reflection amplitude as a function of Δ/Γ' for TLS. The parameter Γ is chosen to be 0.1, 0.5, 1 and 2 respectively. The other system parameter Γ' is fixed as 0.1.

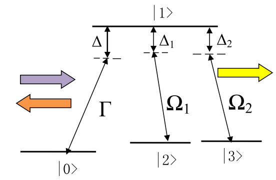

Fig. 3. The energy level scheme of tripod-type four level emitter considered in the present paper.

3. Tunable narrow band spectrum using tripod-type four level emitter system

In the following, we propose a new scheme to overcome the small intensity of narrowed reflective spectrum by using FLS. The configuration of the system is the same as shown in Fig. 1, but with the different optical emitter. The energy level scheme of tripod-type four level emitter is shown in Fig. 3.

In the FLS, the states $|0\rangle$ and $|1\rangle$ have the energies 0(the energy origin)and ω_1 respectively. The propagating single surface plasmon couples to the transition $|0\rangle \leftrightarrow |1\rangle$ with the strength Γ. The excited emitter's state $|1\rangle$ are coupled to the metastable levels $|2\rangle$ and $|3\rangle$ by classical laser beams with Rabi frequencies Ω_1 and detuning Δ_1, and Ω_2 with detuning Δ_2, respectively. The total Hamiltonian in real space can be written as

$$H = H_p + H_e + H_c. \tag{3}$$

Eq. (3) contains three parts, which describes in order: the propagation of the plasmon, the tripod-type four-level emitter, and the couplings

$$H_p = \int dx\,[-iv_g C_R^+ \frac{\partial}{\partial x} C_R + iv_g C_L^+ \frac{\partial}{\partial x} C_L], \tag{4}$$

$$\begin{aligned} H_e = {} & (\omega_1 - i\gamma_1)|1\rangle\langle 1| + (\omega_1 - \Delta_1 - i\gamma_2)|2\rangle\langle 2| + (\omega_1 - \Delta_2 - i\gamma_3)|3\rangle\langle 3| \\ & + \Omega_1/2(|1\rangle\langle 2| + |2\rangle\langle 1|) + \Omega_2/2(|1\rangle\langle 3| + |3\rangle\langle 1|), \end{aligned} \tag{5}$$

$$H_c = \int dx \Gamma \delta(x)[(C_L^+(x) + C_R^+(x))|0\rangle\langle 1| + (C_L(x) + C_R(x))|1\rangle\langle 0|], \tag{6}$$

where v_g is the group velocity of the plasmons and can be simplified as the velocity of the light [2]. The operators $C_R^+(x)$ $[C_L^+(x)]$ represent the bosonic operators creating a right(left-propagating) surface plasmon modes at x coordinate. Here we assume that a linear and nondegenerate dispersion relation holds over the relevant frequency range, and that a plasmon comes from the left with energy $E_k = kv_g$.

The stationary state of the system can be written as

$$\begin{aligned} |E_k\rangle = {} & \int dx\,[\phi_{k,R}^+(x) C_R^+(x) + \phi_{k,L}^+(x) C_L^+(x)]|0, 0\rangle + a_1|0, 1\rangle + a_2|0, 2\rangle \\ & + a_3|0, 3\rangle. \end{aligned} \tag{7}$$

It should be indicated that the single photon process defines a conservation rule of the total occupation number, which means that the photon exists in the surface plasmon modes or that the emitter is in the excited states or in one of the two metastable states. The coefficients $a_n (n = 1, 2, 3)$ are the probability amplitudes of the emitter in the corresponding states respectively.

For a plasmon incident from the left, $\phi_{k,R}^+(x)$ and $\phi_{k,L}^+(x)$ take the forms