Photonics and Nanostructures – Fundamentals and Applications 30 (2018) 25–29

Contents lists available at ScienceDirect

Photonics and Nanostructures – Fundamentals and Applications

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

State transition control of emitter chain coupled to surface plasmon polariton

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ARTICLE INFO

Article history:
Received 31 May 2017
Received in revised form 16 January 2018
Accepted 12 April 2018
Available online 16 April 2018

Keywords:
Two level system
Emitter chain
Surface plasmon polariton

ABSTRACT

In this paper, the behavior of the coupled emitters inside a monochromatic laser field is investigated. The Hamiltonian of the system is obtained using the tensor product of the single emitter Hamiltonian and adding the interaction terms. The population of the states for each emitter is calculated by numerical solving of the time dependent Schrodinger equation. The results show that the transition occurs at a resonance frequency for any values of laser intensity. Also, the resonance frequency depends on the coupling strength of the system. Furthermore, the transition probability increases with increasing the laser intensity at each laser frequency and coupling strength.

1. Introduction

The interaction between the free electron in the surface of the metals and the electromagnetic field creates the surface plasmon polariton (SPP) that has been of interest to many research groups [1–7]. Some of SPPs that spatially confined with metallic nanostructures are called localized surface plasmon polaritons (LSPP) [1]. The sub-wavelength SPPs are used for miniaturization of photonic elements which are introduced as the next generation of information carriers [2,3]. The strong coupling between excitons and SPPs enhances the photoluminescence of the nano silicon crystals that is needed for developing optoelectronic devices [4]. Due to the sub-wavelength dispersion, LSPPs provide interesting applications such as electromagnetic energy transfer at the nano-scale, nano-focusing and several others [5–7]. On the other hand, the quantum emitters typically are multi-level systems that can couple to SPPs and produce the interesting phenomena [1,8,9]. The investigation on the coupling between SPPs and quantum emitters in nonlinear regime is interesting because they create a good opportunity to light control at the nano-scale and manipulating the optical properties of nano-materials [10–12].

Other applications for such systems are including the implementation and manipulation of quantum light and create optical nonlinearity which are essential for quantum network and quantum information [13,14]. The investigation of these systems help us to understand the physics underlying excitations, localize emission, quantum state communication, entanglement, surface enhanced Raman scattering optical tweezers for single molecules, photovoltaic and so on [10–16]. Very recently probing the dark excitons based on SPP near-field spectroscopy has been done experimentally. This kind of spectroscopy significantly improves the capabilities for studying the exciton dynamics, and realizing the active meta-surfaces and the robust optoelectronic systems [17].

In practical models for describing the atom-light interaction, the atom is considered as a two-level quantum mechanical system and the incident field as a classical electromagnetic wave [18]. These models are appropriate approximation for the frequencies limited to the single atomic transition [18]. This two level basis is applied to simulate the macro-spin rotating systems including the spin tunneling coupled to the nano-resonator and entanglement of the tunneling spin [19–23]. Furthermore, the two level quantum system interacting with classical wave is well known as the Landau-Zener model. The single and coupled chains of two level systems in the presence of the time dependent magnetic field have been subject of many studies such as interacting qubit system, quantum dot molecules and etc. [24–30].

In this work, we study the coupling between a triple-chain of quantum emitters and SPPs. The Hamiltonian is constructed by adding the mutual interactions to the tensor product of the single emitters. Also, the effects of the physical parameters such as the coupling strength, laser frequency and the Rabi frequency on the transition probability are investigated.

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https://doi.org/10.1016/j.photonics.2018.04.006
1569-4410/

2. Theory

The semi-classical description is used to study the coupling between SPPs and quantum emitters [1,18]. In this approach, the emitters considered as two-level quantum systems with energy levels E_g (ground state energy) and E_e (excited state energy). Also, the corresponding electromagnetic field of the SPP that stimulates the electric dipoles is treated classically. The Hamiltonian of the interaction between emitters and laser radiation is given by [1,18]:

$$H = H_E + H_{LE} = \tfrac{1}{2}E_e\left(I+\sigma_z\right) + \tfrac{1}{2}E_g\left(I-\sigma_z\right) + \hbar\Omega_0\cos(\omega t)\sigma_x \qquad (1)$$

where ω is the frequency of the incident field, I is unit matrix, σ_x and σ_z are the Pauli matrices. $\Omega_0(=E_0\bullet d)$ is the Rabi frequency where E_0 is the electric field amplitude and d is the electric dipole moment that connects the two levels [18].

In this work, the one dimensional triple chain of emitters with nearest-neighbor interaction is considered. The triple chain of emitters is the smallest building block to extend the results near critical points for one dimensional systems [31–33]. The schematic picture of the coupled emitters is shown in Fig. 1. The interaction between emitters could be described as a tensor product of Pauli's matrices [25,27].

$$H_{\text{int}} = J\sum_i \sigma_{iz}\sigma_{(i+1)z}, \qquad (2)$$

in which J is the interaction strength between two particles that is equivalent to the dipole-dipole interaction of atoms. Therefore, the total Hamiltonian is given by:

$$H_{total} = H_E + H_{EL} + H_{\text{int}} = \tfrac{1}{2}E_e\left(I+\sigma_z\right) + \tfrac{1}{2}E_g\left(I-\sigma_z\right) + \hbar\Omega_0\cos(\omega t)\sigma_x + J\sum_i \sigma_{iz}\sigma_{(i+1)z} = \tfrac{1}{2}\hbar\omega_0\sigma_z + \hbar\Omega_0\cos(\omega t)\sigma_x + J\sum_i \sigma_{iz}\sigma_{(i+1)z} + C, \qquad (3)$$

$$H = \begin{pmatrix} 3E_e+2J & \hbar\Omega_0\cos(\omega t) & \hbar\Omega_0\cos(\omega t) & 0 & \hbar\Omega_0\cos(\omega t) & 0 & 0 & 0 \\ \hbar\Omega_0\cos(\omega t) & 2E_e+E_g & 0 & \hbar\Omega_0\cos(\omega t) & 0 & \hbar\Omega_0\cos(\omega t) & 0 & 0 \\ \hbar\Omega_0\cos(\omega t) & 0 & 2E_e+E_g-2J & \hbar\Omega_0\cos(\omega t) & 0 & 0 & \hbar\Omega_0\cos(\omega t) & 0 \\ 0 & \hbar\Omega_0\cos(\omega t) & \hbar\Omega_0\cos(\omega t) & E_e+2E_g & 0 & 0 & 0 & \hbar\Omega_0\cos(\omega t) \\ \hbar\Omega_0\cos(\omega t) & 0 & 0 & 0 & 2E_e+E_g & \hbar\Omega_0\cos(\omega t) & \hbar\Omega_0\cos(\omega t) & 0 \\ 0 & \hbar\Omega_0\cos(\omega t) & 0 & 0 & \hbar\Omega_0\cos(\omega t) & E_e+2E_g-2J & 0 & \hbar\Omega_0\cos(\omega t) \\ 0 & 0 & \hbar\Omega_0\cos(\omega t) & 0 & \hbar\Omega_0\cos(\omega t) & 0 & E_e+2E_g & \hbar\Omega_0\cos(\omega t) \\ 0 & 0 & 0 & \hbar\Omega_0\cos(\omega t) & 0 & \hbar\Omega_0\cos(\omega t) & \hbar\Omega_0\cos(\omega t) & 3E_g+2J \end{pmatrix} \qquad (4)$$

where $\hbar\omega_0(=E_e - E_g)$ is the energy difference between the emitter's levels and $C(=1/2(E_e+E_g)I)$ is a constant. The population of levels is obtained by numerically solving the time-dependent Schrödinger equation. Here, the free boundary condition is assumed, therefore the first and last emitters are considered exactly the same.

For more clarity, two time independent parameters are introduced by elimination the time dependency of the ground sated wave function. The minimum of the population (MP) and the time averaged population (TAP) of the ground state are defined as follows:

$$MP(T) = Min\left(\left|\psi_{gs}(t)\right|^2\right) \quad t\in[0,\,T] \quad ,TAP(T) = \frac{1}{T}\int_0^T \left|\psi_{gs}(t)\right|^2 dt, \qquad (5)$$

where MP = 1 indicates that there is no transition, while MP = 0 means that at least one complete transition from ground state to exited states occurs. Furthermore, the averaged time elapsed in each level could be express by TAP in which the TAP = 1 (TAP = 0) means the system is in the ground state (excited state) at all times.

Overall, by simultaneously considering these two parameters, we can present a clear picture of transition between states and remaining time of states in each level.

$$H = \begin{pmatrix} 3E_e+2J & \hbar\Omega_0\cos(\omega t) & \hbar\Omega_0\cos(\omega t) & 0 & \hbar\Omega_0\cos(\omega t) & 0 & 0 & 0 \\ \hbar\Omega_0\cos(\omega t) & 2E_e+E_g & 0 & \hbar\Omega_0\cos(\omega t) & 0 & \hbar\Omega_0\cos(\omega t) & 0 & 0 \\ \hbar\Omega_0\cos(\omega t) & 0 & 2E_e+E_g-2J & \hbar\Omega_0\cos(\omega t) & 0 & 0 & \hbar\Omega_0\cos(\omega t) & 0 \\ 0 & \hbar\Omega_0\cos(\omega t) & \hbar\Omega_0\cos(\omega t) & E_e+2E_g & 0 & 0 & 0 & \hbar\Omega_0\cos(\omega t) \\ \hbar\Omega_0\cos(\omega t) & 0 & 0 & 0 & 2E_e+E_g & \hbar\Omega_0\cos(\omega t) & \hbar\Omega_0\cos(\omega t) & 0 \\ 0 & \hbar\Omega_0\cos(\omega t) & 0 & 0 & \hbar\Omega_0\cos(\omega t) & E_e+2E_g-2J & 0 & \hbar\Omega_0\cos(\omega t) \\ 0 & 0 & \hbar\Omega_0\cos(\omega t) & 0 & \hbar\Omega_0\cos(\omega t) & 0 & E_e+2E_g & \hbar\Omega_0\cos(\omega t) \\ 0 & 0 & 0 & \hbar\Omega_0\cos(\omega t) & 0 & \hbar\Omega_0\cos(\omega t) & \hbar\Omega_0\cos(\omega t) & 3E_g+2J \end{pmatrix} \qquad (4)$$

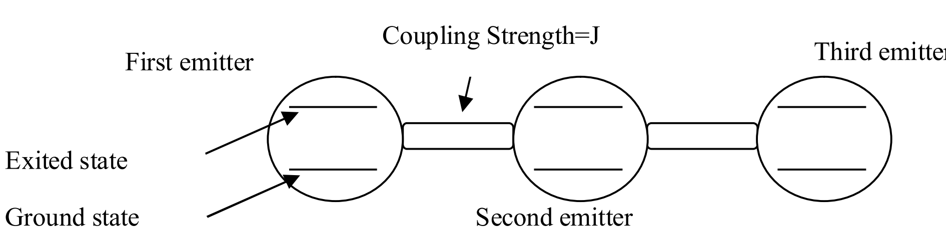

Fig. 1. The schematic picture of a triple chain of quantum emitters.