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Array of nanoparticles coupling with quantum-dot: Lattice plasmon quantum features

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ABSTRACT

In this study, we analyze the interaction of lattice plasmon with quantum-dot in order to mainly examine the quantum features of the lattice plasmon containing the photonic/plasmonic properties. Despite optical properties of the localized plasmon, the lattice plasmon severely depends on the array geometry, which may influence its quantum features such as uncertainty and the second-order correlation function. To investigate this interaction, we consider a closed system containing an array of the plasmonic nanoparticles and quantum-dot. We analyze this system with full quantum theory by which the array electric far field is quantized and the strength coupling of the quantum-dot array is analytically calculated. Moreover, the system's dynamics are evaluated and studied via the Heisenberg-Langevin equations to attain the system optical modes. We also analytically examine the Purcell factor, which shows the effect of the lattice plasmon on the quantum-dot spontaneous emission. Finally, the lattice plasmon uncertainty and its time evolution of the second-order correlation function at different spatial points are examined. These parameters are dramatically affected by the retarded field effect of the array nanoparticles. We found a severe quantum fluctuation at points where the lattice plasmon occurs, suggesting that the lattice plasmon photons are correlated.

1. Introduction

In the recent years, metal nanoparticles (NPs) with the plasmonic properties are considered as indispensable components in a wide range of the different applications [1–4]. These applications are based on the plasmon response of the nanostructures and enhancement of the local electric fields at their surfaces [4–6]. Plasmon resonance studies usually start with the investigation of the NPs interaction with an incidence wave. This feature will be very powerful by merging their properties such as plasmon-plasmon interaction, which opens a new field with high sensitive applications [5,6]. For plasmon-plasmon interactions, it is better to consider the NPs dimer optical properties. In dimer, when NPs inter-distance is decreased, due to the NPs near-field interaction effect, the high intensity localized plasmonic is generated at the gap between the two NPs. The arisen amplitude, actually, depends on the NPs inter-distance and dimer morphological properties [5,6]. Therefore, by increasing the NPs inter-distance, the introduced plasmon resonance at the gap region is decreased dramatically. More importantly, the extinction and scattering resonance peak is hardly alterable by the NPs inter-distance manipulation. It has to be noted that the manipulation of the NPs morphological and NPs inter-distance cause shifting the plasmonic resonance frequency. The control this shift is a very difficult task. In this regard, for sensitive applications such the single molecule detection, the nanostructure plasmon frequency should be precisely controlled. In recent years, several useful works have been conducted on the nanostructures containing 1-D or 2-D chains of the plasmonic NPs [7–9]. This type of plasmon is a modified version of plasmon in which the NPs near-field plasmon resonance interacts with the photonics modes. In other words, the lattice plasmon is generated due to the interaction of the NPs plasmonic field with the photonic modes which creates a unique mode like a laser. The chain of plasmonic NPs enable the far-field photonic modes easily interact with the NPs plasmonic mode. It is notable that with engineering the NPs size, array structure, NPs inter-distance, and polarization direction, it is possible to manipulate and control the nanostructure plasmon resonance frequency. The optical properties of this nanostructure provide an indispensable key in the more attractive biomedical applications [8]. The significant properties of this type of plasmon were the main motivations of the present study for studying the quantum feature of this novel phenomenon. Several related works have been done for investigation of the surface plasmon wave-particle duality

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[10–12]. For example, the single surface plasmon polaritons, caused by the excitation via a single photon, exhibit both wave and particle properties [10]. Also, in another work, it has been shown that the surface plasmon polaritons can be used for the double-slit experiments, which allow observing anti-bunching and self-interference by a single plasmon. Another work showed simultaneous imaging of spatial interference and the quantization of such confined plasmonic fields [11]. In the present study, we initially investigate an array of combined plasmon by full quantum theory and then study the lattice plasmon effect on the quantum-dot (QD). The lattice plasmon effect on Purcell factor, as a novel case, was investigated in the current work. For this purpose, we describe a closed system containing the NPs array and QD. Moreover, in the case of lattice plasmon quantum features, we define the lattice plasmon uncertainty for pairs of location and momentum operators. Finally, as an important quantum feature of lattice plasmon, the second-order correlation function [13,17] is defined to study the correlation states between the interacted photons with QD. In the following, the system dynamics analysis and handling the Heisenberg-Langevin and Maxwell-Bloch equations for the present system are studied.

2. Theoretical and background

In this section, the theoretical study is carried out to provide a better understanding of the electrodynamics of the array of NPs. For this purpose, we theoretically investigate the NPs array that shows new a resonance known as the lattice plasmon that has hybrid properties of the photonic mode and NPs plasmonic. Among the attractive properties of the lattice, plasmon is a very narrow plasmon line-width and its enhanced intensity. Another interesting feature of the lattice plasmon is the delocalization of the plasmon interaction over a large number of particles. In an array, the localized plasmon resonance is produced by each NPs in the near-field, which is the source of scattering, while the array periodicity determines which scattered wavelengths will lead to the constructive interference. In fact, in this nanostructure, the plasmon resonance is delocalized over a large number of particles; the scattering resonance overlapping is destructive at so many incidence wavelengths, while at a few of them, the interference is constructive. This behavior explains the very narrow line-width of the present nanostructure. This case (Fig. 1) illustrates that by the incidence of a wide line-width wave (multiple colors) that interacts with the array of NPs, a lattice plasmon with a very narrow line-width is created. Fig. 1 also presents the wave-particle duality of the array plasmon resonance attributed to the constructive and destructive interference. In essence this figure shows two important things: 1. Lattice plasmon can act as a laser which means that $\Delta\omega \gg \Delta\omega'$; 2. Retarded field effect which is unique for the lattice plasmon, and surly cannot be arisen by a traditional plasmon resonance. In the present study, to define the lattice plasmon, the coupled dipole (CD) method [9] is used by which a framework through the physical insights regarding the far-field optical properties can be understood. In the CD method, each particle is treated as the dipole form in the chain and all the mutual interactions among them are considered. From Fig. 1, we investigate N_p particles, where j is the particles number and r_j represents the position of the particle. Moreover, P_j is the induced dipole moment for each particle, which is proportional to the particle polarizability (α_p) and the localized field $P_j = \alpha_p.E_{local,j}$ where $E_{local,j}$ is the sum of the incidence and retarded fields of the other dipole particles field. Moreover, in this figure, by a simple illustration, N_p-1 particles retarded fields' effect is shown on any particles. Overall, the array plasmon interaction with the near-field plasmonic and the effect of the arrangement periodicity on the constructive interference of the scattering can be understood by the array retarded fields. At any considered wavelength (λ), each localized particle field is equal to [7–9]:

$$E_j = E_{inc,j} + E_{dipole,j} \rightarrow E_{inc,j} - \sum_{\substack{j=1 \\ j\neq i}}^{N_p} A_{ij}\cdot P_j \tag{1}$$

where the retarded fields among dipoles in the chain are defined as [8,9]:

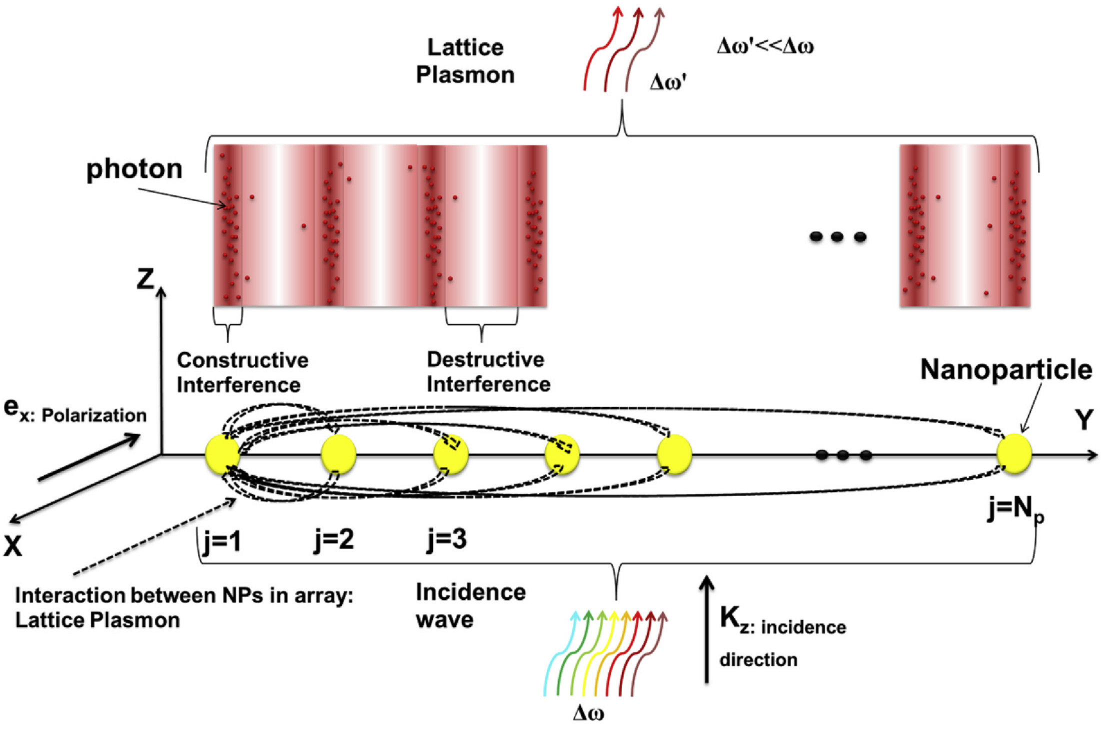

Fig. 1. Schematic of array of NPs arranged in the Y-direction (chain direction); Black-dashed arrows illustrate the plasmonic NPs interaction in array (retarded field effect); in all simulation incidence wave polarization is considered in x-direction and perpendicular to the chain direction; actually this figure schematically shows the lattice plasmon optical properties such as acting as a laser ($\Delta\omega$» $\Delta\omega'$), and wave-particle duality (constructive interference at specific points).