Optik 126 (2015) 101–106

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

The effect of an external quantum electric field on the surface plasmons of a nano-system

T. Ghannam [a,*], Ahmed Mohamed El-Toni [a,b]

[a] King Abdullah Institute for Nanotechnology, King Saud University, Riyadh 11451, Saudi Arabia
[b] Central Metallurgical Research and Development Institute, CMRDI, Helwan, 11421 Cairo, Egypt

ARTICLE INFO

Article history:
Received 18 December 2013
Accepted 2 August 2014

Keywords:
Nano
Lasers
Plasmonics
Sensors
PBG

ABSTRACT

In this paper I investigate the effect that a quantized electric field will have on the surface plasmons of nano particle embedded within PBG material and excited by a two-level system. This study will show that when the external field is fully quantized, a new term will contribute to the damping constant of the radiation emitted from the nano particle. This term does not emerge from the system when the electric field is treated classically. Even though this extra term should increase the line width of the light emitted from the system, nevertheless, the overall effect of the external field is to reduce the line width of the emitted light. I also investigate the ability of the system to work as a plasmonic photo-sensor.

1. Introduction

Surface plasmons are a very hot topic these days, especially on the nano-level where they exhibit many novel properties and promising applications. Their applications range from nano-lasers [1–5] to chemical or bio-sensors [6,7] etc.

One problem of surface plasmons is their fast decay rate, especially for those excited on metallic surfaces, which could reach around 10^{-15} s. Prolonging the life of the plasmons will consequently shrink the spectral width of the light emitted by them, rendering them much more efficient, especially as sources of light, e.g. nano-lasers.

In a previous paper [4] it was shown that introducing an external electric field to a system made of a nano-particle (NP) excited by a two-level system (TLS), the width of the spectrum of light emitted from this system will decrease by about two orders of magnitude. In another paper, it was shown that the spectral width can be reduced greatly, about three orders of magnitude, by embedding the system of the NP and the TLS in a PBG material [5].

In this paper, I show that by combining both; the PBG and the external field, their effects will combine resulting in a big reduction in the spectral width. Moreover, I show that by treating the external field quantum mechanically, a new term will contribute to the decay constant of the NP. This new term is completely quantum mechanical as it does not show up when the electric field is treated classically as in paper [4]. However, and for the parameter regime used in this paper, the effect of this new term will turn up to be very small.

Moreover, and as the changes the external electric filed will induce in the spectral width of the system can be used to extract information about the same external field, I investigate the ability of the system to work as plasmonic photo-sensor (Fig. 1).

2. Equations of motion

The Hamiltonian of the system can be written as follows:

$$H = \hbar\omega_0 a^\dagger a + \frac{\hbar\omega_2}{2}\sigma_z + V(t) + H_r + H_i + H_e \tag{1}$$

* Corresponding author.
E-mail address: gtalal@hotmail.com (T. Ghannam).

http://dx.doi.org/10.1016/j.ijleo.2014.08.137

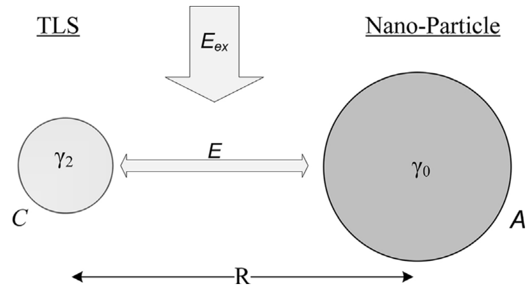

Fig. 1. The nano-system configuration.

where $a^\dagger$ and a are the raising and lowering operators for the plasmons' amplitude of the NP [1]. σ_z is the matrix operator for the population difference between the two levels of the TLS. $V(t)$ is the dipole–dipole interaction potential between the TLS and the NP [2]. H_r is the self-energy of the heat reservoirs to which the system is coupled, and H_i describes the coupling between these reservoirs and the system.

The interaction potential $V(t)$, H_r, and H_i are given as follows:

$$\begin{aligned}
&V(t) = -\overrightarrow{E_i}\times\hat{\mu}_2 = \hbar\Omega\left[\sigma_-(t)a^\dagger(t) + \sigma_+(t)a(t)\right], \quad \Omega = \frac{1}{4\pi\varepsilon_m}\left[\frac{\mu_0\times\mu_2 - 3\left(\mu_0\times\vec{r}\right)\left(\mu_2\times\vec{r}\right)}{R^3}\right]\\
&H_r = \hbar\sum_j \omega_j\left(A_j^\dagger A_j + C_j^\dagger C_j\right)\\
&H_i = \hbar\sum_j\left[g_{0j}Z_0\left(A_j a^\dagger e^{-i\omega_{j0}t} + A_j^\dagger a e^{i\omega_{j0}t}\right) + g_{2j}Z_2\left(C_j\sigma_+ e^{-i\omega_{j2}t} + \sigma_- C_j^\dagger e^{i\omega_{j2}t}\right)\right]\\
&H_e = -B\mu_0 Z_0\left(a^\dagger b e^{-i\omega_{e0}t} + b^\dagger a e^{+i\omega_{e0}t}\right) - \mu_2 Z_2 B\left(\sigma_+ b e^{-i\omega_{e2}t} + b^\dagger\sigma_- e^{+i\omega_{e2}t}\right)
\end{aligned} \tag{2}$$

E_i is the interaction electric field between the NP and the TLS; Ω is the coupling strength between the NP and the TLS [2]; μ_0, μ_2 are the dipole matrix elements for the NP and TLS, respectively. The A operator corresponds to the heat reservoir responsible for the combined effects of electromagnetic radiation and thermal phonons on the NP life time, along of being the reservoir for the external electric field, while the C operator corresponds to the heat reservoir responsible for the combined effects of electromagnetic radiation, thermal noise, and electronic pump noise contribution to the decay and de-phasing of the TLS.

The $\sigma_\mp$ are the raising and lowering operators of the electronic transitions of the TLS.

g_{0j} and g_{2j} are the coupling constants of the NP and the TLS to their heat reservoirs A and C, respectively. In this paper I neglect the decay of the external electric field into the A- or C-reservoirs, hence, I set $g_{ej} = 0$.

Z_0 and Z_2 are called the "*form factors*" and they incorporate the effect of the PBG material in the Hamiltonian. The form factors are given by the following expression [8]: $Z(\varepsilon_{ij}{}^\pm) = (\varepsilon_v - \varepsilon_{ij}{}^\pm)/[(\varepsilon_c - \varepsilon_{ij}{}^\pm) + \kappa^2]$ where ε_{ij} are the energy of the polariton and given by $\varepsilon_{ij}{}^\pm = 1/2(\varepsilon_v - \hbar\omega_{ij}) \pm [(\varepsilon_v - \hbar\omega_{ij})^2 + 4\hbar\omega_{ij}(\varepsilon_v - \varepsilon_c)]^{1/2}$ with ij runs for the active atomic levels of the NP, and ε_v and ε_c are the upper and lower band energies of the PBG material, respectively. The $(+)$ sign is used when the energy levels of the NP and the the TLS reside within the upper band of the energy gap of the PBG medium while the $(-)$ sign is used when they reside within the lower band. In this paper I use the $(+)$ sign assuming that the energy levels of the NP and TLs residing on the upper band. κ is the relaxation constant of the PBG medium [8].

The external electric field is give by the full quantum expression [9]:

$$E_{\text{ex}} = B\left(be^{-i\omega_e t} + b^\dagger e^{+i\omega_e t}\right) \quad \text{where} \quad B = i\sum_k\sum_\lambda e_{k\lambda}\sqrt{\left(\frac{\hbar\omega_k}{2\varepsilon_0 V}\right)} = i\sum_k\sum_\lambda g_e(k\lambda) \tag{3}$$

Using Heisenberg equation of motion, the plamson amplitude operator will take the preliminary form:

$$\frac{\mathrm{d}a(t)}{\mathrm{d}t} = -i\Omega\sigma_-(t) - iZ_0\sum_j g_{0j}A_j + \frac{i}{\hbar}\mu_0 Z_0 Bbe^{-i\omega_{e0}t}$$

To find the drift term of this equation, I use the Langevin formalism [10] where the drift term is defined as follows:

$$\left\langle D_a(t)\right\rangle = -\hbar^{-2}\int_0^\infty \mathrm{d}\tau\left\langle[H(t+\tau),[H(t),a(t)]]\right\rangle_A = -\hbar^{-2}\int_0^\infty \mathrm{d}\tau\left\langle\left[H(t+\tau), -\hbar\Omega\sigma_-(t) - \hbar Z_0\sum_j g_{0j}A_j + \mu_0 Z_0 Bbe^{-i\omega_{e0}t}\right]\right\rangle_A$$

The brackets indicate that I am taking the average over the A-reservoir only.

The above expression will translate into the following:

$$= -\hbar^{-2}\int_0^\infty \mathrm{d}\tau\sum_j g_{0j}^2\hbar^2 Z_0^2\langle a\rangle_A e^{-i\omega_{j0}(t+\tau)} - \int_0^\infty \mathrm{d}\tau B^2 Z_0^2\mu_0^2\left\langle a(t+\tau)b^\dagger(t+\tau)e^{i\omega_{e0}(t+\tau)}, b(t)e^{-i\omega_{e0}(t)}\right\rangle_A$$