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Journal of Luminescence 112 (2005) 151–155
JOURNAL OF LUMINESCENCE
www.elsevier.com/locate/jlumin

Optically induced force between nano-particles irradiated by electronic resonant light

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Available online 26 November 2004

Abstract

We theoretically study the characteristic properties of the optically induced force (OIF) between two semiconductor nano-particles (SNPs) irradiated by an electronic resonant light, assuming that they are floating in the fluid medium. The exerted force is calculated by the surface integral of the Maxwell stress tensor (MST). The response field in MST is obtained by using the discretized integral equation, which can be applied to the plural nano-objects with arbitrary shapes. One of the remarkable results is as follows: we reveal that the bonding state (BS) and the antibonding state (AS) in the polaritonic molecule (PM) can be excited if two SNPs exist near each other. Each state is selectively excited by an incident light with a particular polarization. The attractive OIF arises when BS is excited, while the repulsive OIF arises when AS is excited. This finding will open the way to mechanically control the collective motion of assembly of SNPs manipulating the nanoscale spatial structures of the radiation field through the resonant excitation.

PACS: 78.40.Fy; 78.67.Bf; 78.67.Hc; 78.90.+t

Keywords: Optical manipulation; Radiation force; Resonance

1. Introduction

The force arising from the mechanical interaction between matter and light is called ‘radiation force’ or ‘optically induced force (OIF)’, which is utilized in the optical manipulation for the control of the spatial configuration and the mechanical motion of small objects floating in the fluid medium [1]. The radiation force on nano-objects under electronic resonance condition is an unexplored subject to be studied because of its potentialities for applications in nano-technology.

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0022-2313/$ - see front matter
doi:10.1016/j.jlumin.2004.09.015

Recently, we have theoretically proposed a new type of optical manipulation of semiconductor nano-particles (SNPs) using excitonic resonance conditions [2], where the peculiar properties of radiation force reflecting the quantum characteristics of the respective SNPs depending on their size, shape and quality, are used for sorting out NPs with particular quantum properties. Although we treated an isolated SNP in our previous works, the study of the OIF between SNPs is also important because it provides fundamental information on the dynamics of SNP assembly irradiated by electronic resonant light. On the other hand, there are lots of studies about the optical properties of the electronic systems confined in the quantum dots (QDs) [3]. QD is often called the 'artificial atom' because the electronic excitation levels are discrete like those of the atoms. Recently, the coherent coupling of two QDs has been observed, and this system is called 'artificial molecule' [4]. Since the vertically aligned, self-assembled QDs embedded in the layer structure of semiconductor are used in the experiments, the above effect is not linked with the mechanical motion of QDs. However, if the target SNPs are floating in the fluid medium, such a situation greatly affects the relative motion of SNPs. If we clarify the linkage between the coherent coupling of two QDs and their mechanical motions, it would open the door to control the collective motion of assembly of SNPs by resonant laser light. The purpose of this contribution is to demonstrate such a study.

2. Calculation methods

The OIF is obtained by performing the surface integral of Maxwell stress tensor (MST) as

$$\langle \boldsymbol{F} \rangle = \left\langle \int_s \mathrm{d}S \ \overset{\leftrightarrow}{\boldsymbol{T}} \cdot \boldsymbol{n} \right\rangle, \tag{1}$$

where $\langle\rangle$ is the time average, $\overset{\leftrightarrow}{\boldsymbol{T}}$ is the stress tensor, i.e., $\overset{\leftrightarrow}{\boldsymbol{T}} = \mathbf{EE} + \mathbf{HH} - (1/2)(|\mathbf{E}|^2 + |\mathbf{H}|^2)\overset{\leftrightarrow}{\boldsymbol{I}}$, and $\boldsymbol{n}$ is the unit outward normal vector on the surface surrounding object (S). In this expression, $\mathbf{E}$ and $\mathbf{H}$ are electric and magnetic fields satisfying Maxwell equation, and $\overset{\leftrightarrow}{I}$ is the unit tensor [5]. Response fields in MST are calculated by the discrete dipole approximation (DDA) improved with complex-conjugate gradient algorithm to solve linear simultaneous equations and fast-Fourier-transform techniques to evaluate the convolution integral [6]. DDA is based on the solution of the Maxwell equations in the form of a discretized integral equation, where the scatterer is divided into polarizable N_p meshes as

$$\mathbf{E}(i,\omega) = \mathbf{E}^0(i,\omega) + \sum_{j=1}^{N_\mathrm{p}} \mathbf{G}^{\mathrm{med}}(i-j,\omega)\cdot\mathbf{P}(j,\omega)V_j. \tag{2}$$

In this equation, i and j are the indices of meshes at observation and source positions, respectively, $\mathbf{E}(i,\omega)$ is the self-consistent field as a solution of Maxwell equation, $\mathbf{E}^0(i,\omega)$ is the incident field, $\mathbf{G}^{\mathrm{med}}(i-j,\omega)$ is the dyadic Green function of homogeneous medium, V_j is the volume of ith mesh, and $\mathbf{P}(i,\omega)$ is the induced polarization whose definition is $\mathbf{P}(i,\omega) = \chi(i,\omega)\mathbf{E}(i,\omega)$, where $\chi(i,\omega)$ is the local susceptibility. Putting $\mathbf{E}(i,\omega) = \chi(i,\omega)^{-1}\mathbf{P}(i,\omega)$ in l.h.s. of Eq. (2), it is reduced to be linear simultaneous equations of $\mathbf{P}(i,\omega)$ as $\sum_j \mathbf{A}(i-j)\cdot\mathbf{P}_j = \mathbf{E}_i^0$.

Thus, we obtain the internal fields in the scatterer by solving Eq. (2), in the first stage. In

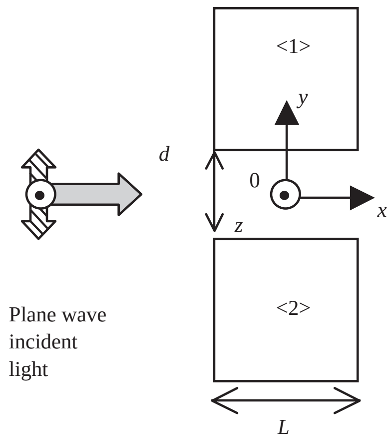

Fig. 1. Geometry of the calculation. The center of each cubic is in the x–y-plane ($z=0$). Each SNP has the same size. In the numerical evaluation of OIF on each SNP, z- or y-polarization is considered.