J. At. Mol. Sci.
doi: 10.4208/jams.060311.071011a

Vol. **3**, No. 2, pp. 152-159
May 2012

Optical transmission through strongly coupled gold nanoparticle arrays with structural defects

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Received 3 June 2011; Accepted (in revised version) 10 July 2011
Published Online 8 November 2011

Abstract. We present a strongly coupled gold nanoparticle arrays with planar defect structures and numerically investigate its the transmission properties We show that two kinds of distinct resonant modes, the plasmonic resonant mode and the defect mode, appear in the forbidden photonic band gap. It is found that the plasmonic resonant mode can be controlled by introducing the planar defect, while the peak value and the width of the defect mode depend strongly on the defect distance.

PACS: 42.25.Bs, 73.20.Mf, 73.63.-b

Key words: structural defect, transmission spectra, plasmonic resonant mode, defect mode

1 Introduction

The optical properties of metallic nanoparticles and their arrays have been a subject of continuous attention [1, 2]. Along with the fast progress of modern lithographic technique [3], the MNPs and their arrays have a wide variety of applications of nanoscale devices in chemistry [4], biology [5] and applied physics [6]. Some of the most important features of metallic nanoparticles array are the existence of forbidden photonic band gaps and the strong enhancement of an incident field [7] at the plasmon resonance frequency on or near the particle surface, when the light frequency matches the frequency of collective oscillations of the conduction electrons in the particle. The enhancement of an incident field at special frequency is commonly explained by resonant excitation of surface Plasmon [7–10].

Surface plasmons have been intensively studied since a number of decades already. They are surface charge density waves, with an associated electromagnetic field, propagating along the interface between a dielectric and a metal. Surface plasmons can be categorized into two types: localized plasmon resonances, in which incident light is absorbed or scattered by the oscillating electric dipoles within a metal nanoparticle; and surface plasmon polaritons, which

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propagate along metal surfaces in a waveguide-like fashion until released at some distance from their point of origin. The former are important for generating local field factors, which enhance linear and nonlinear optical effects near the metal surface. Particle surface plasmons can be excited in nanoparticles of free-electron like metals, such as Au and Ag, resonance peaks are observed at particular frequencies. In particular, the resonant frequencies of the particle plasmons depend mainly on their composition and shape [11–14].

Dielectric structure with various defects, for example, point and line defects [15–17], can be utilized as optical functional devices, such as waveguides [18, 19], channel add/drop filters [20, 21], and light emitting devices [21]. An advantage of both metallic and metallo-dielectric structures versus pure dielectric structures is the possibility of opening wide photonic gaps with a small number of periods, thus leading to more compact geometries necessary for applications [22]. Most studies have been emphasized on properties of line and point defects. However, research for planar defects in 3D structures is seldom [23]. In our previous work [24], we had investigated the basic optical properties of the metallic nanoparticle array with different center to center distance between adjacent particles and different radius of the particles. It is showed that the plasmon resonant modes appear in the photonic forbidden band gap (PFB) and interparticle coupling plays a major role in the properties of the particle plasmon. In this paper, we shall introduce the planar defects to the periodic nanoparticle array, and study the basic properties of planar defects, such as the defect modes in the metallic nanoparticles array. When we introduce the planar defects, the input beam is modulated by the planar defects. So the planar defects can significantly affect the energies of plasmon resonances of the metallic nanoparticle array.

2 Model and theory

The finite difference time domain (FDTD) method was used to simulate the filed propagation. FDTD has been widely used as a fundamental tool in microwave engineering. Electromagnetics is governed by the time-dependent Maxwell's curl equations

$$\begin{aligned}\frac{\partial H}{\partial t} &= -\frac{1}{\mu(r)}\nabla\times E,\\ \frac{\partial E}{\partial t} &= \frac{1}{\epsilon(r)}\nabla\times H - \frac{\sigma(r)}{\epsilon(r)}E,\end{aligned} \tag{1}$$

where E and H are electric and magnetic fields respectively, and $\epsilon(r)$, $\mu(r)$ and $\sigma(r)$ are the permittivity, permeability and electric conductivity of the material, respectively.

The dielectric constants of metals at optical frequencies are complex numbers because of the absorption, and in most cases the real part of the dielectric constants are negative. The frequency-dependent optical properties of the metallic nanoparticles array are approximated by the Drude model, which defines the dispersive permittivity as

$$\epsilon(\omega) = \epsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma_p}\right). \tag{2}$$