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Light-Driven Acoustic Band Gap Based on Metal Nanospheres

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Abstract. In this paper, light-driven acoustic band gap is presented by considering two metal nanospheres illuminated simultaneously by laser and acoustic waves. The interaction between the photonics and phonons is investigated through optical distribution force, van der Waals distribution force, and acoustic pressure upon these nanospheres. Based on the optical force and van der Waals force, the acoustic form functions for the metal nanoaggregates with different optical intensity are calculated, and the light-driven acoustics band gap at low frequency band has been found. It is shown that the band gap width can be widened with increasing the incident laser intensity, or by using proper metal materials and background media. This could provide potential applications in optical nanoswitches and acoustical filters.

1. Introduction

Recently single-molecule surface enhanced Raman scattering (SM-SERS) has attracted much attention [1-3]. SERS phenomena are associated with excitation of surface plasmon resonances of metallic nanoparticles (NPs), and it is generally believed that SERS arise at junctions between closely spaced NPs. Driven by potential applications in optics, electronic or magnetic data storage, an important research effort has been directed towards the study of these size-controlled metallic NPs [4]. The properties of NPs differ from the bulk metal properties due to the fact that fraction of atoms resides on the NPs surface and the finite size of the particles changes both electronic and structural properties. Excitons, plasmon-polaritons and confined phonons are typical excited states of these NPs, which have been shown to give rise to the collective properties. More recently, nanoacoustic waves have been generated at terahertz frequencies when semiconductor quantum-well nanostructures are illuminated by femtosecond laser pulses, and it is possible to manipulate the coherent acoustic phonons in the both temporal and spatial domains [5].

Therefore, the study and understanding of the interaction between photonics and phonons at the nanoscale is very important, which represents one of the fundamental challenges of nanotechnology.

In this paper, the interaction between photonics and phonons is investigated through two metal nanospheres illuminated simultaneously by laser and acoustic waves. The acoustic form function for the metal nanoaggregates with different optical intensity is obtained, in which the light-driven acoustics band gap at low frequency band is found.

2. Theoretical analysis

A system of two metal spheres is illuminated by a plane acoustic wave and an incident optical intensity simultaneously. The geometry of the problem as well as the notations used are shown in Fig. 1. Let the origin of the spherical coordinate system (r,θ,φ) located at the centre O, and two spherical coordinate systems (r_1,θ_1,φ) and (r_2,θ_2,φ) are also defined for the two spheres and, respectively, referred to their centers O_1 and O_2 which are separated by a distance d. The propagation vector $\mathbf{k}$ of the incident plane acoustic wave is perpendicular to the Oy-axis and forms an angle α with the Oz-axis.

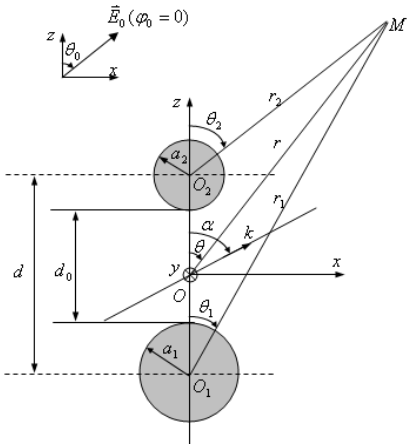

Fig. 1 Two-sphere coordinate systems

For this system, the two nanospheres are illuminated simultaneously by incident laser and acoustic waves. Thus elastic force and optical force are derived, respectively, from the incident intensity of acoustic waves and the electromagnetic-field intensification that occurs near the particles. Meanwhile, the van der Waals force is exerted on the same particles at nanometers separation. These forces might modify the precise geometry of the metallic nanoaggregates and therefore might change the transfer characteristics of the acoustic waves. In this section, the optical force, van der Waals force, and acoustic pressure upon these nanospheres are calculated step by step, and then the transfer characteristics of the acoustic waves are investigated.

The first step in calculating optical force between two metal nanospheres is to obtain the potential between them. Due to the size of the nanoparticles is very small compared to the optical wavelength, this allows us to neglect retardation and therefore solve the Laplace equation, rather than Maxwell's equations [6]. Once the potentials are obtained, by taking the derivative the radial stress distribution upon the nanospheres can be calculated out [7]. Based on Hamaker formula [8], the van der Waals force can also be formulated. Last the technique of multiple scattering [9] is used to treat the acoustic scattering, and the form functions are calculated theoretically in this paper.

3. Calculation results and discussions

The total form function depend on the optical distribution force, VDW distribution force, acoustic pressure, nanoparticle materials, and background medium.

The wavelength-dependent dielectric constant $\varepsilon(\omega)$ was directly taken from the bulk experimental data in Palik's book [10]. Our following calculations are all for two $a_1 = a_2$ = 30 nm nanoparticles and only for the case of end-on incidence (α =0, θ=0) with the acoustic wave vector $\mathbf{k}$ perpendicular to the photon wave vector $\mathbf{k}_o$. Here we are not considering size dependent dielectric response for small particles whose diameter is close to the bulk electron mean free path (size effect is significant for particle diameter less than 5 nm) [11].

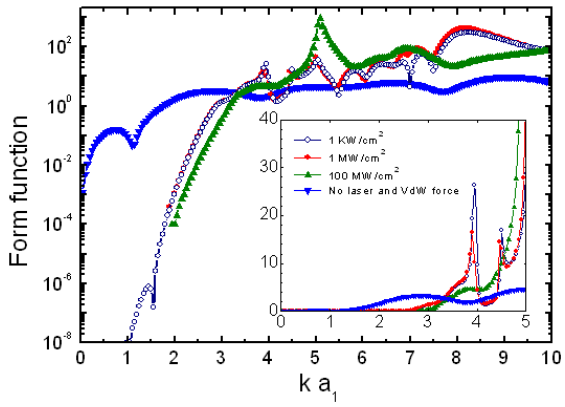

Fig.2 Computed form function of two Ag spheres under different laser intensities at 514-nm wavelength versus ka_1 for the separation distance d_0 = 1 nm in air. An expanded view in linear scale is shown in the inset.

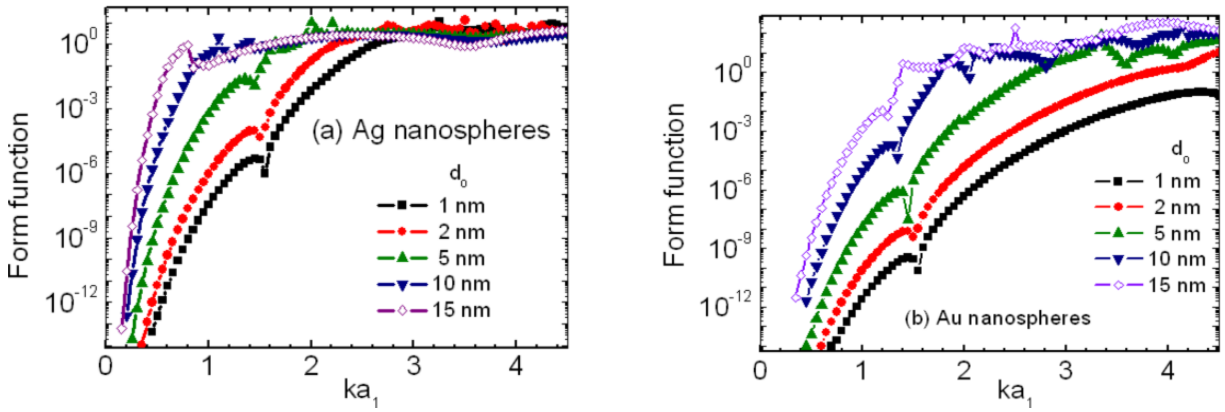

Fig. 3 Computed form function of two elastic spheres at end-on incidence (α =0, θ=0) versus ka_1 for different separation distances: (a) for Ag nanospheres, (b) for Au nanospheres.

Figure 2 shows the computed far field form function of two 60 nm-sized Ag spheres versus the non-dimensional acoustic wave number ka_1, at a closing separation distance d_0= 1 nm under different optical incidence intensities at 514-nm wavelength in air. At this very closing separation distance, the optical distribution force and the VDW distribution force are much more important than the acoustic pressure upon the sphere surfaces, which results in an acoustic band gap at the low frequency band. Here the Hamaker constant of Ag is taken as $A = 4\times10^{-20} J$. The width of the band gap is increased as the incidence intensity grows. At resonant conditions acoustic signal in the field of laser radiation can be enhanced by a few orders of magnitude.

Figure 3(a) shows the computed form function of two 60 nm-sized Ag spheres in air under $1\,KW/cm^2$ optical intensity at 514-nm wavelength for different separation distances. With the separation distance is increasing, the optical force and VDW force are both decreased, and the band gap width is becoming small. Meanwhile, the form function of two 60 nm-sized Au spheres in water with an intensity of 5 MW/cm^2 at 800-nm wavelength is shown for different separation distances in Fig. 3(b). The Hamaker constant for Au is $10\times10^{-20}J$, which is 2.5 times larger than that of Ag. When the separation distance is increased, the VDW force between Au NPs does not decrease as rapidly as it does between Ag NPs, thus the band gap width for Au particles is much larger than that for Ag particles.

From the above results, the light-driven acoustics band gap at low frequency band is presented, due to the optical force, van der Waals force, and acoustic pressure upon these nanospheres. This light-driven acoustics band gap could provide potential applications in optical nanoswitches and acoustical filters.

4. Conclusions

The acoustic scattering field from two metal nanospheres illuminated by laser and acoustic waves simultaneously is investigated. In the process of considering this interaction between photonics and phonons, optical force and van der Waals distribution force are calculated, as well as the far field form function. It is shown that the acoustic form function of the metal nanoaggregates under some optical intensity presents a large light-driven acoustics band gap at low frequency band, which could provide potential applications in optical nanoswitches and acoustical filters. On the other hand at resonant conditions acoustic signal in the field of laser radiation can be enhanced by a few orders of magnitude.

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