The Interparticle Coupling Effect on Plasmon Resonance Properties of Magnetite@Au Magnetoplasmonic Nanoparticles

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Abstract

Magnetoplasmonics based on Composite nanostructure, has been used in sensing, optical devices and optical switching. Magnetite@Au core@shell nanostructure exhibits both plasmonic and magnetic properties and holds promise for using in biomedical applications. The ability to control optical properties of magnetite@Au over a broad spectral range and adjustable composite thickness make these nanostructures an important subject for magnetoplasmonic studies. In this research, interparticle coupling effect on plasmon resonance properties of magnetite@Au magnetoplasmonics nanoparticles by using finite element method has been calculated. In addition optical characteristic of magnetite@Au strongly depend on size, surrounding medium and pitches between the particles. The effects of these parameters on optical properties of magnetite@Au nanostructures have been studied. The calculated results show plasmon resonance absorption peak has changed from 576 nm to 540 nm by decreasing size of Au coating from 5 nm to 17 nm. Moreover, by increasing magnetite core diameter from 10 nm to 25 nm, wavelength of maximum plasmon resonance absorption has been changed 590 nm to 620 nm. As the refractive index of medium around magnetite@Au increasing, results have shown a red shift absorption peak which the peak position linearly depends on the refractive index of medium. The effects of coupling between two magnetite@Au core@shell on plasmon resonance peak have been calculated. The results demonstrate when magnetite@Au nanoparticles pitches are shorter than the surface plasmon attenuation length, the surface plasmons couple to each other, thus it is creating new modes that differs from the usual dispersion relation of surface plasmons. Therefore, simulated results have showed wavelength of maximum absorption for coupled magnetite@Au at 506 nm which is different from single magnetite@Au core-shell and demonstrates about 80 nm blue shift. These results could be employed for design of plasmonic sensors with tunable optical properties especially with interparticle coupling in presence of magnetic field.

Keywords: Core-shell, Magnetoplasmonic, Surface plasmonic resonance;

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1. Introduction

Nanostructures with combining both magnetic and plasmonic properties become an active research topic in recent years, Armelles et al. (2013), Maksymov et al. (2015). Nanoparticles made of noble metals like Ag and Au exhibit surface plasmonic resonance (SPR) under special conditions. Plasmonic effects enhance absorbance and scattering at plasmonic resonance. Moreover, the intensity and position of plasmon resonance in absorbance spectrum depend on the shape, size and the embedding medium. SPR has been used for biosensing, photothermal therapy applications, Brullot et al. (2012), Conde et al. (2011). The ability of magnetical manipulating and guiding of nanostructure are important in biomedicine. Magnetic materials such as magnetite and maghemite have been used in biomedicine due to low toxicity and high magnetic susceptibility, Brullot et al. (2012). Core-shell noble metal-magnetic nanoparticles provide both magnetic and plasmonic behaviors. Therefore, these composites have great potential due to multifunctionalities. Fe3O4@Au nanoparticles are promising structures for using in biomedical applications due to their magnetic and plasmonic characteristics. Fe3O4@Au can be prepared by available chemical methods in different diameters of shell and core. Therefore, desire optical properties can be achieved at manageable dimensions. These multifunctional structures have extensive applications such as using them for magnetic resonance imaging (MRI), drug release and photothermal therapy, Brullot et al. (2012), Conde et al. (2011). In this work, Optical properties of Fe3O4@Au nanoparticles such as absorbance spectra and surface plasmonic resonance wavelength were calculated. The effect of size, surrounding medium and interparticle coupling on these optical properties was studied. Optical spectra for arbitrary geometry can be calculated by finite element method, finite difference method. In this research, finite element method has been chosen for calculating optical properties of Fe3O4@Au particles.

2. Calculation method

Absorbance spectra as a function of wavelength for core-shell nanospheres were calculated through Maxwell equations, Jackson (1998).

\[ \nabla \times \mu^{-1} (\nabla \times E(r, \lambda)) - k_0^2 \left( \varepsilon_r - \frac{i \sigma}{\omega \varepsilon_0} \right) E(r, \lambda) = 0 \]  

(1)

Where \( \mu \) is relative permeability, \( \varepsilon_r \) is relative permittivity, \( \varepsilon_0 \) is vacuum permittivity, \( k_0 \) is wave vector and \( \sigma \) is conductivity. Moreover, absorbed power in the particle is defined as \( Q \), Danaei et al. (2015).

\[ Q = \int J(r, \lambda) \cdot E(r, \lambda) dv \]  

(2)

Where \( J \) is current density induced by electromagnetic waves and \( E \) is electric field. Dielectric constants of gold and magnetite are given from, Brullot et al. (2012). Radii of shells and cores, dielectric constant of surrounding medium have been used as variables. Polarization of incidence light is transverse electric field (TE), as represented \( E_z = \exp(ik_0x) \) in z direction, has applied to structures. As it is shown in Fig. 1. Because of symmetry it is simulated a quarter of core-shell nanospheres. \( x \) is the direction of wave vector of the light. It is applied in x-z plane of spheres \( n \times H = 0 \) as boundary condition. It imposes symmetry for electric field. Perfectly matched layer is applied to the outer layer.
3. Results and Discussions

As stated in the previous sections, absorbance spectra as a function of wavelength and the unit of absorbance in all figures are Watt. As the plasmonic absorbance is depending on size of nanoparticles, for investigating the effect of core radius, the shape and other optical characteristics remain constant and the core radius is changed between 10 nm to 25 nm. As it is shown in Fig. 2, by increasing the core radius, position of absorbance peak changed from 590 nm to 620 nm and the peaks of spectra get broaden. The behavior is as expected, because when core radius is increased the effect of plasmonic resonance is decreased. However, total radius is increased. Consequently, the intensity of absorption peak gets increased. Moreover, red shift can be explained by coupling plasmonic resonance modes of outside and inside of shell.

As the gold shell gets thicker, the location of absorbance peak blue shifted. This phenomenon can be considered that thinner shells facilitate the coupling plasmon modes of outside and inside. Also, the intensity of thinner shell gets decreased for core radius of 10 nm. In Fig. 3, it is shown that the radius of core is constant and the thickness of shell gets increasing from 5 nm to 17 nm. As the thickness of shell is 5 nm the position of peak absorption is about 576 nm, by getting thicken, the position of peak absorbance in wavelength blue shifted and the peak position changed to 540 nm.
As it is explained before the surrounding medium of core@shell nanoparticles can be effect of the location of peak absorbance. Therefore, refractive index is third variable parameter. Fig. 4 n described as refractive index and radius of core is 10 nm and thickness of shell is 15 nm. By changing the refractive index from 1 to 2.5, the location of peak absorption red shifted in wavelength from 541 nm to 718 nm.

In Fig. 4 it is shown absorbance spectra for different surrounding media. It is notable that by changing refractive index from 1 to 1.2, the position of peak is varied from 541 nm to 551 nm as obviously seen from the inset of Fig. 4.
The effect of interparticle coupling between plasmon modes can be investigated by changing the distance between two particles. \( d \) is the distance between two centers of the particles. Comparing one nanoparticle with two nanoparticles in Fig. 5 shows that absorbance peak of wavelength blue shifted from 588 to 506 nm and the intensity gets increased although changing the distance from 60 nm to 160 nm center to center does not affect on the location of peak absorption and just intensity get increased.

Fig. 5. Absorbance spectra as a function of wavelength for different distance from 60 nm to 160 nm centre to centre. \( d \) is the distance between two centres of nanoparticles. By increasing distance, intensity increased. Also in this figure the absorbance spectrum of one particle is shown. Interparticle coupling between plasmon modes cause blue shift of peak absorption and increasing the intensity. The unit of absorbed power is Watt.

4. Conclusion

\( \text{Fe}_3\text{O}_4@\text{Au core@shell} \) can be tuned their optical properties due to changing the radius of core or shell and surrounding medium. By increasing the core radius (10, 15, 20, 25), location of absorption peak red shifted and varied from 590 nm to 620 nm. Also, the peaks of spectra got broaden. This was because of the effect of plasmonic resonance is decreasing. Moreover, red shift of absorbance peak in wavelength can be explained by coupling plasmonic resonance modes of outside and inside of shell. Second variable parameter is shell thickness. As the gold shell got thicker, blue shift occurred (the absorption peak changed from 576 nm to 541 nm). The reason was coupling plasmon modes of outside and inside happened faster in thinner shells. Also, the intensity of thinner shell got decreased. Furthermore, it was shown that \( \text{Fe}_3\text{O}_4@\text{Au} \) with shell layer = 15 nm and core radius = 10 nm was very sensitive to the changing of medium. By changing refractive index from 1 to 1.1, the position of peak absorption changed from 541 nm to 551 nm. Finally, to study of interparticle plasmon modes in this paper, absorption spectrum of one particle with one particle compared and it was shown that by interparticle coupling the blue shift occurred and the peak shifted from 588 nm to 506 nm.

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