Control of the Hot Spot Localization in Graded Plasmonic Nano-Antennae.

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Abstract

We consider nano-antennae comprising metallic nanospheres of different sizes organized in graded linear chains in the proximity of a heterointerface of two media with different refractive indices. We address the near field signal of the antennae under the excitation by evanescent waves and show that the response of the array is localized at a few nanospheres, creating a hot spot. We demonstrate that, even for a fixed wavelength, the position of the hot spot can be controlled by the angle of incidence of the excitation. This opens new opportunities to control electromagnetic energy localization and enhancement at nanoscale.

1. Introduction

Arrays of metal nanoparticles, operating as plasmonic antennae, have been studied extensively during the last decade (see, e. g. Ref. [1]). One particular type of such systems is a linear array of nanoparticles of variable size. Different designs of these arrays have been studied, in particular the Yagi-Uda antennae [1] or linearly graded arrays of nanospheres [2] (which is analogous to a broadband log-parametric antenna). These nanodevices convert excitation optical signals into plasmon modes or vice versa. The electric field can be enhanced by orders of magnitude in the vicinity of these nano objects. Often, such enhancement occurs in a small volume forming so called hot spot. Recently, we demonstrated that the position of the hot spot in graded arrays can be controlled by changing the wavelength of the excitation [2]. In this contribution, we show that the hot spot position can easily be controlled by angles of incidence of the excitation beam even at a fixed wavelength.

2. Results

We consider a system schematically sketched in Fig. 1: a linear graded array of 15 silver nanospheres (NSs) at a glass/indium tin oxide (ITO) interface, using the following material and geometrical parameters: the refractive index of glass is $n_1 = 1.5$, that of ITO is $n_2 = 2.1$, the frequency dependent permittivity of silver is taken from Ref. [3], particle radii r_i vary from 45 to 31 nm by 1 nm step, their center-to-center distances d_i are chosen in such a way that the ratio $d_i/r_i = 24/5$ is a constant while center-to-interface distance are $z_n = 140$ nm.

We assume that the array is embedded in the medium 1 (above the interface) and is illuminated by a plane wave incident from below (from the denser ITO medium 2) at the polar angle θ, measured from the normal pointing into the medium 2, and the azimuthal angle ϕ, measured from the axis parallel to the chain and pointing from the largest to the smallest sphere. We consider values of $\theta > \theta_B$ exceeding

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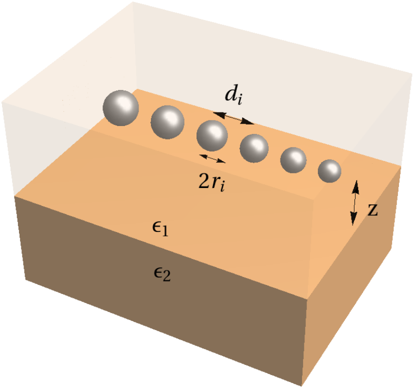

Fig. 1: Schematics of the system: a graded nano-antenna at a heterointerface with a dielectric contrast.

the critical angle of the total reflection θ_B. Such scheme of excitation by evanescent waves can be advantageous for applications and can easily be realized in experiments.

For our set of parameters the point-dipole approximation can be used. The induced dipole moment $\mathbf{p}_n$, which gives the amplitude of the secondary (scattered) field in the vicinity of the nano sphere n, is then given by the solution of the following system of linear equations:

$$\mathbf{p}_n = \alpha_n(\omega)\left[\mathbf{E}_n^{ex} + \sum_{n\neq m} \widehat{\mathbf{G}}_{nm}^{(0)}\,\mathbf{p}_m + \sum_{n\neq m} \widehat{\mathbf{G}}_{nm}^{(r)}\,\mathbf{p}_m\right] \tag{1}$$

where $\alpha_n(\omega)$ is frequency and size dependent polarizability of the n-th sphere (we follow Ref. [2] to calculate these quantities), $\mathbf{E}_n^{ex}$ is the excitation evanescent field at the n-th particle, $\widehat{\mathbf{G}}_{nm}^{(0)}$ is the Green's tensor of the direct dipole field in the medium 1 and $\widehat{\mathbf{G}}_{nm}^{(r)}$ is the Green's tensor of the reflected dipole field which arises due to the dielectric contrast at the heterointerface. To calculate the latter we used the approach of Ref. [4].

In Fig. 2 (left panel), we show the squared moduli of the induced dipole moments as functions of the particle number n and the azimuthal angle of the excitation ϕ. The system is illuminated by an s-polarized plane wave (with the wavelength $\lambda = 535$ nm) incident from below at $\theta = 50° > \theta_B$. The right panel presents $|\mathbf{p}_n|^2$ for three particular values of ϕ. The figure demonstrates that by changing the

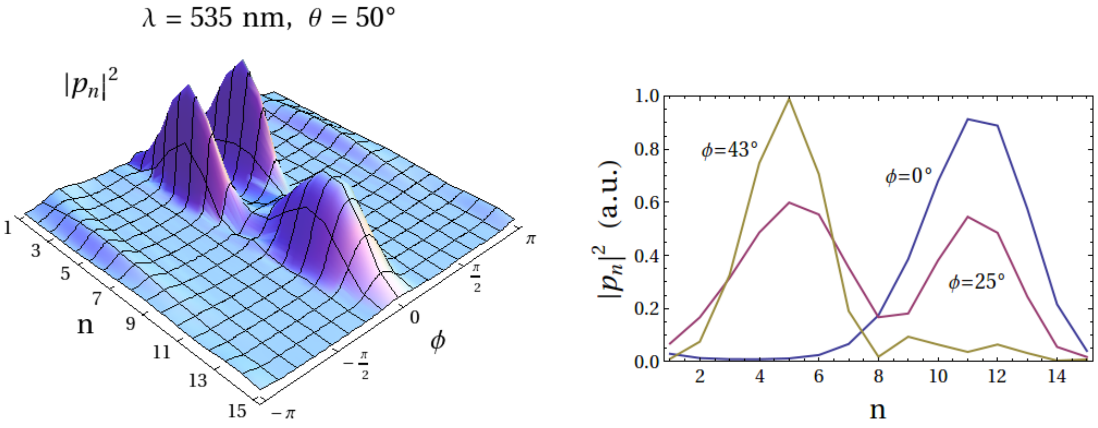

Fig. 2: Induced dipole moments as a function of the azimuthal angle of incidence ϕ.

azimuthal angle ϕ one can control the position of the hot spot, shifting it from one extreme of the array to the other.

Finally, we note that graded arrays operate as broad band nano-antennae responding within almost the whole range of the visible spectrum; the hot spot location in such systems can be controlled by the wavelength of the excitation [2]. Such possibility is partially related to the dependence of the resonance frequencies of different spheres on the their sizes. Here, we use a fixed wavelength, however, by changing the azimuthal angle we change the effective wavelength, because the phase difference of the incoming field at the spheres depends on the angle. Our results demonstrate clearly that this phase difference plays a very important role for the system response, it can even overcompensate strong resonance effects. The latter underlines the importance of interference and retardation effects for response characteristics of nano antennae.

4. Conclusions

In conclusion, we have theoretically studied the optical response of graded chains of noble metal nanospheres in the proximity of a glass/indium tin oxide interface. We found a strong dependence of the response signal of such plasmonic antennae on the direction of incidence of the incoming field. The response signal is strongly localized forming a hot spot: the full width at half maximum of the signal measures typically a few center-to- center distances. We showed that the position of the maximum can be switched from one extreme of the array to the other (shifting by more than a μm) by adjusting the azimuthal angle of incident light at a fixed frequency. The latter opens possibilities of additional control of the electromagnetic energy enhancement and localization suggesting that graded plasmonic arrays are promising candidates for building blocks of subwavelength optical devices.

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