Controlling Radiation Patterns of Plasmonic Nano-Antennae

J. Munárriz[1,2], A. V. Malyshev[1,*], V. A. Malyshev[2], and J. Knoester[2]

[1] GISC, Departamento de Física de Materiales, Universidad Complutense
Avda Complutense s/n, E-28040 Madrid, Spain
Fax. +34 91 3944547; e-mails: j.munarriz@fis.ucm.es, a.malyshev@fis.ucm.es
[2] Centre for Theoretical Physics and Zernike Institute for Advanced Materials
University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands
Fax: +31 50 363 4947; e-mails: j.knoester@rug.nl, v.malyshev@rug.nl
[*] *on leave from* A. F. Ioffe Physical-Technical Institute, St. Petersburg, Russia

Abstract

Radiation patterns of linear chains of metallic nano-particles (nano-antennae) in the proximity of a hetero-interface of two media with different refractive indices are studied theoretically. We propose to excite the system by evanescent waves in which case the excitation does not interfere with the radiated signal. We show that the radiation pattern of such antennae can be very anisotropic and can easily be designed and controlled not only by the system geometry but also by external parameters, such as the wavelength, polarization and/or angles of the excitation beam. The proposed device can operate therefore as a tunable nanoscopic source of light with high and tunable directionality.

1. Introduction

Recently, plasmonic antennae have received a great deal of attention (see Ref. [1] for a review). These devices, being arrays of metallic nano particles, convert propagating optical signals into plasmon modes, and vice versa, at the nanometer scale. One of the challenging tasks is to control and manipulate radiation patterns of such antennae. These arrays are usually assumed to be embedded into a homogeneous dielectric host. In this contribution we show that the radiation pattern of an antenna placed at a hetero-interface of two materials can be controlled and tuned in a variety of ways, in particular, by the angles of incidence of the excitation beam, giving rise to a highly directional and tunable radiation pattern.

2. Results

We consider a homogeneous array of 15 silver nanospheres (NSs) at a glass/indium tin oxide (ITO) interface. The material and geometrical parameters of the system are as follows: the refractive index of glass is $n_1 = 1.5$, that of ITO is $n_2 = 2.7$, the frequency dependent permittivity of silver is taken from Ref. [2] (for the excitation wavelength $\lambda = 450$ nm which is close to the NS plasmon resonance), particle radii are 20 nm, their center-to-center distances being 60 nm while center-to-interface distance is $z = 60$ nm. To calculate the system response for such geometry, we used the point-dipole approximation in combination with the approach of Ref. [3] and obtained exact Green's tensors for interaction fields between induced particle dipoles, containing contributions of both incident and reflected fields.

We assume that the array is embedded in a glass 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 of the chain. We consider values of $\theta > \theta_B$ exceeding the critical angle of the total reflection θ_B. Such scheme of

ISBN 978-952-67611-0-7

excitation, by evanescent waves is advantageous for both measurements and applications because only the antenna field contributes to the radiation above the interface; the excitation does not mask out the antenna radiation. This illumination scheme is experimentally simple to realize too.

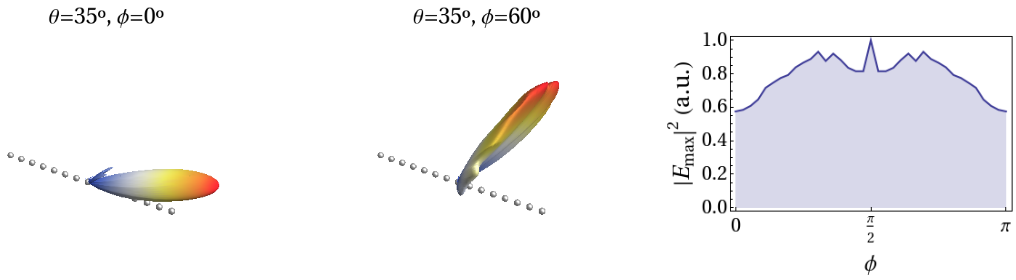

Fig. 1: Radiation patterns of the antenna described in the text. The system is illuminated by an s-polarized plane wave coming at the polar angle $\theta = 35°$ (which is just about 3° above the angle for total reflection) and various azimuthal angles ϕ. The rightmost plot shows the maximum radiation intensity as the function of ϕ.

In Fig. 1, we show polar patterns of the antenna subject to a plane wave incident at $\theta = 35° > \theta_B$ and various ϕ. The figure demonstrates that by changing the azimuthal angle ϕ of the excitation we can change the polar angle of radiation. The rightmost panel, where the maximum radiation intensity is plotted as a function of ϕ, suggests that emission is efficient in the whole range of azimuthal angles. That is not the case if the polar angle of the excitation is further away of θ_B, as can be seen from Fig. 2. The latter figure shows that for more oblique incidences, the range of azimuthal angle, for which the antenna emits efficiently, shrinks considerably.

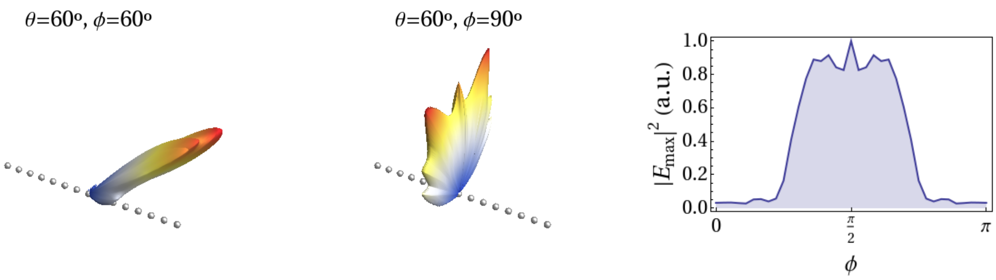

Fig. 2: Same as in Fig. 1 but for $\theta = 60°$.

Another parameter that affects radiation patterns is the polarization of the excitation. As can be seen from Fig. 3, the structure of the polar pattern is strongly polarization dependent. We argue therefore that the radiation of the considered nano-antennae can be controlled by the sheer geometry of the excitation and its polarization.

Finally, we note that the geometry of the system itself determines the optical response. In particular, as we increase the number of the NSs in the array the main lobes of the polar pattern become thinner (in the direction corresponding to the polar angle), that is the directionality of the antenna increases. On the other hand, as we change the distance of the chain to the interface, additional modulation of the main lobe emerges (in the direction corresponding to the azimuthal angle).

3. Discussion

In order to qualitatively understand the radiation of the antenna, we can use the stationary phase approximation [4]. If we further consider that the phase of an induced dipole coincides with the phase of the ex-

ISBN 978-952-67611-0-7

Fig. 3: Emission pattern for s-polarized (left) or p-polarized (right) excitation at $\theta = 35°$ and $\phi = 90°$.

ternal electric field at the dipole, then the following expression for the far field at a point $\mathbf{R} = \{R, \Theta, \Phi\}$ arises:

$$\mathbf{E}_{\mathrm{f}} \propto \frac{[\mathbf{p} - (\mathbf{p} \cdot \mathbf{n})\mathbf{n}]\, e^{ikR}}{R} \; \frac{\sin\left[(\widetilde{n} \sin\theta \cos\phi - \sin\Theta \cos\Phi)\; N\, d/2\right]}{\sin\left[(\widetilde{n} \sin\theta \cos\phi - \sin\Theta \cos\Phi)\;\; d/2\right]} \; \left(e^{-i \cos\Theta \cdot z} \pm s(\Theta) \cdot e^{i \cos\Theta \cdot z}\right)$$

where $\{\theta, \phi\}$ give the direction of the incident plane wave, $\mathbf{p} \propto \mathbf{E}_{\mathrm{t}}$ is the induced dipole of one NS (which is parallel to the transmitted field $\mathbf{E}_{\mathrm{t}}$), $\mathbf{n} = \mathbf{R}/|\mathbf{R}|$ is the direction of the observation, $\widetilde{n} = n_2/n_1$ is the reduced refractive index and $s(\Theta)$ is the effective image dipole obtained within the stationary phase approximation [4].

In the above expression the first factor gives the far field of a *single* dipole whose direction coincides with that of the excitation field (the transmitted evanescent field $\mathbf{E}_{\mathrm{t}}$ in our case). The second factor arises from the sum of contributions of all induced dipoles of the NSs of the array, while the last one takes into account the contribution of image dipoles (the reflected dipole field). All qualitative features of the radiation patterns can be obtained by analyzing the above formula which turns up to give a good quantitative approximation to the exact polar patterns discussed above. Therefore, the formula can be used to predict or design desired polar patterns basing on the material parameters, system geometry, and that of the excitation.

4. Conclusions

We studied radiation patterns of plasmonic nano-antenna, formed by a linear chain of equally sized silver nano-spheres at a glass/indium tin oxide interface, excited by evanescent waves. We demonstrated that the radiation of the system is very directional. We showed also that the emission pattern of the antenna can be extremely sensitive to polarization and angles of incidence of the excitation beam. Therefore, this device can operate as a tunable nanoscopic source of light with high directionality.

References

[1] L. Novotny and N. van Hulst, Antennas for light, *Nat. Photonics,* vol. 5, p. 83, 2011.

[2] E. D. Palik, *Handbook of Optical Constants of Solids*, Elsevier, 1998.

[3] M. Paulus, P. Gay-Balmaz and O. J. F. Martin, Accurate and efficient computation of the Green's tensor for stratified media, *Phys Rev. E,* vol. 62, 5797, 2000.

[4] W. C. Chew, *Waves and Fields in Inhomogeneous Media*, IEEE, 1995.