Directional Plasmonic Nano-Antennas

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Abstract

We address 2D arrays of metallic nano-particles arranged in a honeycomb lattice in the proximity of a hetero-interface of two media with high dielectric contrast. These systems can function as antennas in the visible range of the spectrum. We demonstrate that their radiation patterns can be made very directional by appropriate choice of the system geometry and materials. We show also that if such an antenna is excited by evanescent waves, the direction of the main radiation lobe can be switched abruptly by changing the polarization of the incident light. Within the proposed excitation scheme the device converts an incident plane wave into a narrow beam, operating as a nanoscopic source of light with tunable directionality.

1. Introduction

Plasmonic antennas, being often arrays of metallic nanoparticles, convert propagating optical signals into the surface plasmon modes or *vice versa* at the nanometer scale. Recently, such antennas for light have received a great deal of attention (see Ref. [1] for a review). Bowtie [2, 3], cross resonant [4], and nanorod [5] configurations have been investigated. Nonlinear plasmonics [6], nanoscale spectroscopy [7] with optical antennas as well as nanoantenna-enhanced gas sensing [8] have also been discussed. In this contribution, we address the problem of the antenna excitation and its radiation control and obtain highly directional and tunable radiation patterns.

2. Results

We consider a 2D array of silver nanospheres arranged in a honeycomb lattice and embedded into a glass matrix above a glass/indium tin oxide flat interface (see left and middle panels of Fig. 1). Refractive

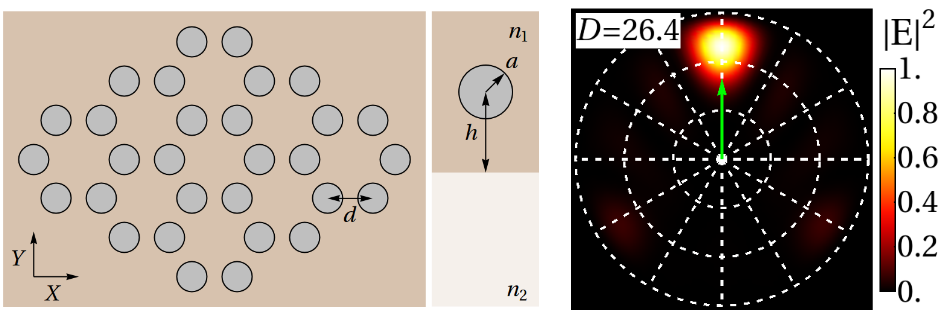

Fig. 1: Schematics of the system: left and middle panels are the top view of the antenna and the side view of one sphere, respectively. Right panel — radiation pattern of the antenna (see text for details).

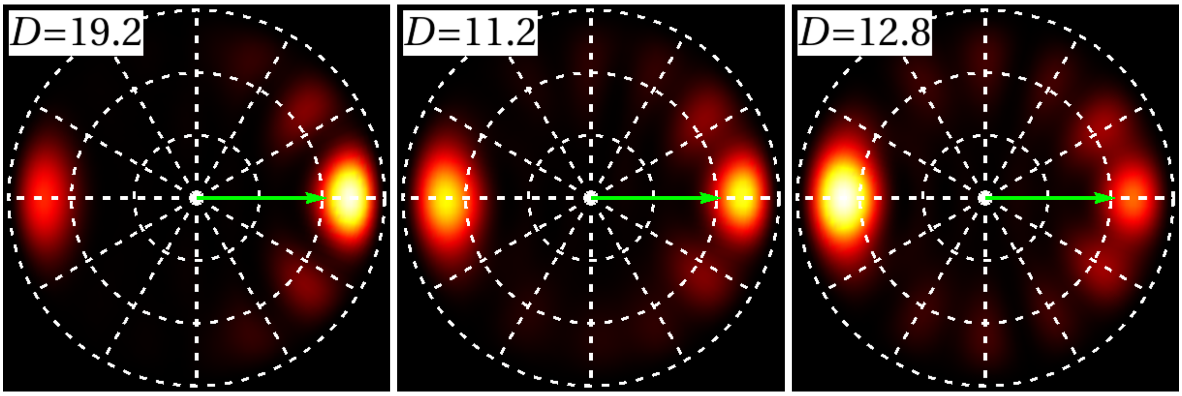

Fig. 2: Radiation pattern for p-polarized (left) or s-polarized (right) and $45°$-polarized (middle) excitation at $\Theta = 63°$ and $\Phi = 0°$. Same color scheme and notations as in Fig. 1.

indices of the two media are $n_1 = 1.5$ (glass) and $n_2 = 2.7$ (indium tin oxide). The dielectric constant of silver is frequency dependent and is taken from Ref. [9] for the excitation wavelength $\lambda = 610$ nm. Particle radii are $a = 40$ nm, their center-to-center distances for nearest neighbors are $d = 120$ nm while center-to-interface distances are $h = 120$ nm. The array can be excited by an incident electric field while we are interested in the secondary field scattered by the system. For the chosen geometry, the point-dipole approximation can be used to calculate the scattered field within the Sommerfeld integral formalism (see, for example, Ref. [10]).

We assume that the array is illuminated by a linearly polarized plane wave incident from the optically denser (lower) medium at the azimuth angle Φ (measured from the X axis) and the polar angle Θ. The latter exceeds the angle of the total reflection, in which case the system is excited by evanescent waves. This is advantageous for both measurements and applications because the antenna radiated field dominates in the far zone above the interface, where the evanescent excitation field is exponentially small, so it does not mask out the useful signal. This illumination scheme is simple to realize in experiment too.

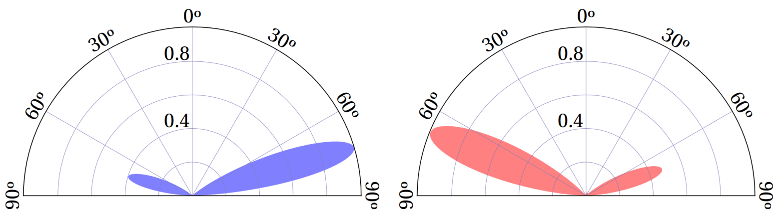

Fig. 3: Cross sections of the polar patterns from Fig. 2 along $\phi = 0°$ for the case of p (left) and s (right) polarizations of the excitation.

Right panel of Fig. 1 shows the polar plot of the antenna radiation pattern. Color gives the far field intensity $|\mathbf{E}|^2$ as a function of the detection angles θ and ϕ. The azimuth angle ϕ changes from 0 to 2π in the standard way, while the polar angle θ changes linearly along the radius from 0 to $\pi/2$ (dashed circle are drawn each $30°$). The system is excited by an s-polarized plane wave with the incidence angles $\Theta = 50°$ and $\Phi = 90°$. The excitation propagation direction is represented schematically by the green vector, its end point has the coordinates (Θ, Φ). The value D, given in the white rectangle, is the directivity of the radiation pattern, *i. e.*, the ratio between the maximum radiation intensity and the average one.

In Fig. 2, we plot polar patterns of the antenna illuminated by a plane wave incident at $\Theta = 63°$ and $\Phi = 0°$ having different polarizations. The figure demonstrates that the direction of the main radiation lobe can be almost reversed by changing the polarization of the excitation from s to p. Fig. 3 gives cross sections of the radiation patterns from Fig. 2 for s to p polarized excitation. As can be seen, in this case the scattering changes from predominantly forward to the backward one.

3. Discussion

The geometry of the system determines its possible optical responses to a large extent. In particular, as the number of the particles in the array increases, the main lobe of the polar patterns tends to become narrower and the directionality of the antenna increases. On the other hand, the possibility to control the direction of the main lobe by the geometry of the excitation and/or its polarization can disappear.

Radiation patterns of the antenna can be understood qualitatively by means of the stationary phase approximation [11]. Assuming also that the phase of an induced dipole coincides with the phase of the external electric field at the dipole, we obtained a closed analytical expression for the far field. This expression is far from compact and we don't present it in this brief communication. Nevertheless, it allows to analyze the radiation patterns in an efficient way and can help to design the geometry of the antenna given a target radiation pattern and properties.

4. Conclusions

We studied radiation patterns of plasmonic nano-antennas comprising 2D arrays of equally sized silver nano-spheres, arranged in a honeycomb lattice near a glass/indium tin oxide interface, excited by evanescent waves. We demonstrated that the radiation of the system can be very directional. The emission patterns of such antennas depend on the polarization and angles of incidence of the excitation beam. We conclude, therefore, that such devices can operate as a tunable nanoscopic source of light with high directionality.

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