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Design and simulation of nano-antenna with tunable direction of radiation

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ABSTRACT

A new concept for tuning direction of radiation in nano-antenna with negative and positive polarizability is introduced and evaluated by numerical simulation. It has shown that such a configuration consisted of an array of nanoparticles can tune the direction of radiation pattern successfully. Increasing the number of nanoparticles exhibits more directivity at special direction. Variation in position of nanoparticles is used to tune the angle of maximum radiation. The maximum tunability for special geometry of three particles is about 40°. Angle of maximum radiation pattern for four particles is shifted from interval 150–180° to 0–30°.

1. Introduction

Light scattering by nanoparticles is one of the interesting fields in nanoscience since it paves the way for many important applications in several areas of biology and medicine (cancer treatments, nano-biosensors, molecular orientation sensing, etc.) [1,2], optical communications [3], solar cells [4], etc. Nowadays, one of the interesting applications of scattering of nanoparticles is to build optical antennas although this area has not been fully studied yet [2–4]. An optical antenna, known as nanoantenna, is a device consisting of nanometer scale metallic particles, which operates in the optical range. In addition to possessing the properties of the conventional antennas, the nanoantennas also benefit from wider bandwidth compared with the traditional antennas. That is because the optical frequency is much higher than the frequency used in the wireless communications. Metal nanoparticles as nanoantennas close to an electromagnetic emitter offer very efficient channels to couple the emitted photons to surface plasmons of the antenna, thus, enhancing considerably the efficiency of the emission. The emitter–antenna distance determines whether the spontaneous emission mostly couples to surface plasmon modes (when the distance is several nanometers) or directly couples to free space modes [5]. Therefore, the far-field emission of the emitter–antenna system is determined by the surface plasmon modes in the antenna, which can be used not only to enhance the emission of the emitter [6] but also, to control the emission direction [7]. The latter property may lead to guide light propagation even down to the single photon level [5]. It has been discussed recently that plasmonic structures exhibit extraordinary capabilities in controlling and manipulating the polarization states of the light. It has shown that plasmonic patch nanoantennas can not only confine light into ultra-small modal volumes but also provide a polarization conversion in the reflection [8]. Besides the mentioned achievements, different set of parameters has been recently introduced to tailor the optical response of nanoantennas such as the impedance and the load of the device. Modification of the radiation scattered by the antenna (intensity and scattering diagram) at a given operating wavelength through modifying the load medium of the nanoantennas in the presence of an external electric field has been demonstrated as an instant [9]. The interesting optical specifications of externally controlled nanoantennas motivate further studies for demonstration of tunable antennas. In this article, we investigate another tunable aspect of nanoantennas: the design possibility of nanoantennas with tunable spatial patterns. From the Mie scattering theory, induced dipole may be stimulated on each particle, which is related to the total electric field upon that particle by a polarizability factor. The polarizability is determined by geometry and material parameters. The polarizability can be very high even though the particle is of deep subwavelength size [10,11].

The nanoantenna design in the optical regime can benefit from the antenna design experiences in microwave domain. For example, a half-wavelength dipole antenna was designed and fabricated according to this manner by Muhlschlegel et al. [12]. In another theoretical study several particles placed near an optical dipole source

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were suggested as a Yagi-Uda-like optical antenna and nanoantennas system with more than one particle as director was designed to achieve narrow beam pattern [13]. It has also been shown that nanoantenna system with array of core–shell nanoparticles located over layered substrate and engineered substrate can manipulate the radiation performance [14]. In [14], it has demonstrated that placing nanoparticles above a substrate can change the radiation performance and layers with different materials as substrate is engineered to tailor radiation beam in special direction. However, such a system design with an array of nanoparticles is not capable of preparing tunable direction of radiation. Among all the studied previous works in this area, none of them consider the possibility of nanoantenna design with tunable direction of radiation pattern.

In this paper, after a brief review of light scattering theory we analyze radiation pattern of the introduced arrays of nanoparticles composed of three and four particles. Moving one particle up or between the other particles has been tailored to perform tunable direction of radiation. Positive and negative polarizability for particles affect the radiation pattern.

2. Theoretical background

Light scattering by a homogeneous, isotropic and spherical subwavelength particle with radius R illuminated by a linearly polarized plane wave can be analyzed using the Lorenz-Mie theory [15,16]. When the particle size is much smaller compared with the incident wavelength (λ), light scattering obtained by Mie theory can be approximated using dipole approximation (DA) [11]. Under this condition, each dipole has polarizability that can be expressed using the Clausius–Mossotti relation [15,17]:

$$\alpha_E = 4\pi a^3 \frac{\varepsilon_1 - \varepsilon_m}{\varepsilon_1 + 2\varepsilon_m} \tag{1}$$

where α_E is electric polarizability, ε_1 and ε_m are the electric permittivity of the particle and surrounding medium. According to (1), the scattered field by particles presents a resonance when $\varepsilon_p = -2\varepsilon_m$ [13,15]. Our analysis has been restricted to response of a nanoparticle to an applied uniform static electric field. Also, particle and surrounding medium have been considered to be nonmagnetic. If size parameter of particle (ka, with k being the wave number and a being the radius) is small, one can approximate the electric dipole moment of a non-interacting particle with $\vec{p} = \varepsilon_0 \alpha_E \vec{E}_0$ where $\alpha_E = 6\pi i a_1/k^3$ is the particle polarizability with $a_1 = -2/3(ix^3) \times (m^2 - 1/m^2 + 2)$ [18]. x is the size parameter, and m is the refractive index of particle. In the above relations, E_0 is the electric incident field and ε_0 is the vacuum electric permittivity.

In the presence of an arrangement of particles, the scattered electric field from each particle includes the effects of the incident field and the field scattered from other particles if the spacing of the particles is small enough. The electric field can be considered as a result of particle interaction with the incident plane wave solely, if the interaction between the particles is negligible. Each dipole has a polarizability α_i (3×3 tensor) is located at position r_i, and has a polarization $P_i = \alpha_i E_i$ with E_i the electric field on dipole i. The induced dipole on each particle is proportional to total field upon that particle which can be expressed as the summation of two terms. The first term is associated to the incident field in the absence of particles and the second term is the electric field due to the coupling between particles [13,14]. The electric field at r_i radiated by a dipole at r_j with polarization p_j is given as:

$$E(r_i) = k^2 (n_{ij} \times P_j) \times n_{ij} \frac{e^{ikr_{ij}}}{r_{ij}} + (3n_{ij}(n_{ij}.P_j) - P_j) \left(\frac{1}{r_{ij}^3} - \frac{ik}{r_{ij}^2} \right) e^{ikr_{ij}} \tag{2}$$

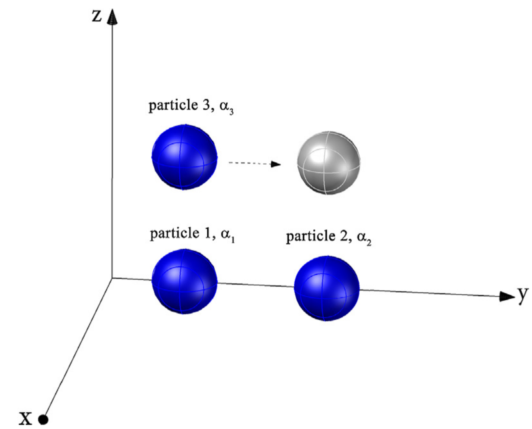

Fig. 1. Configuration of particles, the particle radius is 60 nm and the distance between particles in the y direction is 150 nm ($\varepsilon = 2.01$, $\mu = 1$).

In (2) the dominant terms in the far field are the terms with r^{-1} and in the near field are the terms with r^{-2} and intermediate field are r^{-3} [19]. In Cartesian coordinates Eq. (2) becomes:

$$E(r_i) = \frac{e^{ikr_{ij}}}{r_{ij}} \left(-k^2 (n_{ij} n_{ij} - I) + \left(\frac{1}{r_{ij}^2} - \frac{ik}{r_{ij}} \right) (3n_{ij} n_{ij} - I) P_j \right) \tag{3}$$

where n_{ij} is the direction vector defined by $n_{ij} = r_{ij}/|r_{ij}|$ with $r_{ij} = r_i - r_j$. Also, $n_{ij} n_{ij}$ is the dyadic product and I is 3×3 identity matrix. Each dipole has a polarization $P_j = \alpha_j \times E_j$ where E_j is the electric field at r_j that is due to the incident wave [11]. The electric field on dipole i ($1 \le i \le N$) due to external field $E^\circ(r) = E^\circ \exp(ikr)$ and the field radiated by all other dipoles is [19]:

$$E(r_i) = E^\circ(r_i) + \sum_{j \neq i}^{N} F_{ij} P_j, \quad 1 \le i \le N \tag{4}$$

3. Description of system geometry

Using the dipole approximation (DA) and coupling dipole method (CDM) described in the previous section, we analyze the scattering pattern for several particles forming different geometries. Three particles have been considered, all of which are similar and have electric permittivity of $\varepsilon = 2.01$ and magnetic permeability of $\mu = 1$. Radius of particles have been assumed to be $R = 60$ nm. In Fig. 1 three particles of which two of them are located on y coordinate have been considered where the third particle is moved above them. On the y coordinate particle-to-particle distance is 150 nm and the incident wavelength is 620 nm.

The scattering pattern of the introduced configuration has been shown in Fig. 2 corresponding to specific geometries with positive polarizability for all of particles indicated in Fig. 1. The scattering pattern presents maximum radiation in a specific angular range for introduced geometrics and the radiation direction is shifted in the special interval when the third particle is moved toward the other two particles.

In Fig. 3 the scattering pattern of the particles with negative polarizability for the second particle and positive polarizability for the first and the third particles has been shown.

A similar configuration with four particles has been considered in Fig. 4 where three of them are located on yz plan and one particle moves in the y direction. The distances between the first and the second and also the first and the third particles are 150 nm and 200 nm, respectively.

According to Fig. 5, when the particle moves to the right (in the y direction), radiation pattern of the introduced configuration