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Superdirective all-dielectric nanoantennas: theory and experiment

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Abstract. We introduce a novel concept of superdirective nanoantennas based on the generation of higherorder optically-induced magnetic multipoles. Such an all-dielectric nanoantenna can be realized as an optically small spherical dielectric nanoparticle with a notch excited by a point source located in the notch. We also confirm the predicted superdirectivity effect experimentally through scaling to the microwave frequency range.

1. Introduction

Electrically small radiating systems whose directivity exceeds significantly that of a dipole are usually called superdirective [1]. Superdirectivity is an important property of radio-frequency antennas employed for space communications and radioastronomy, and it can be

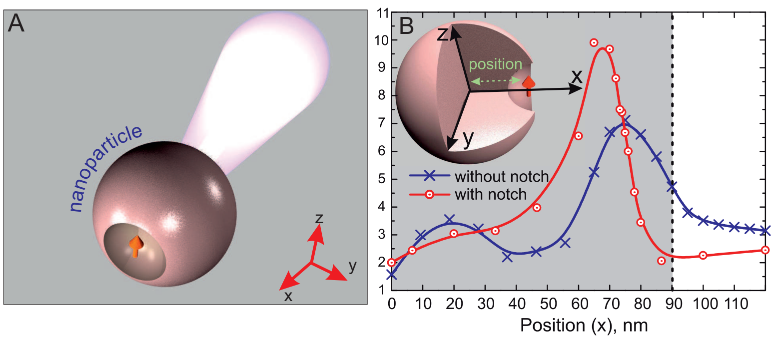

Figure 1. (**A**) Geometry of the notched all-dielectric nanoantenna. (**B**) Maximum of directivity depending on the position of the dipole ($\lambda = 455$ nm) in the case of a sphere with and without notch, respectively.

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achieved in antenna arrays in a narrow frequency range and for a sophisticated system of phase shifters [1]. Achieving high radiation directivity is also important for actively studied optical nanoantennas [2, 3]. Usually, small plasmonic nanoantennas possess weak directivity close to that of a point dipole. Despite its importance, antenna's superdirectivity in the optical frequency range was not discussed or demonstrated so far. Recently, it was suggested to use different dielectric and semiconductor materials for the development of antennas at the nanoscale [4, 5, 6]. Such all-dielectric nanoantennas consist of high-permittivity nanoparticles having both resonant electric and magnetic optical responses [4, 5, 6]. This approach allows to study an optical analogue of the so-called Huygens source, an elementary emitting system with properly balanced electric and magnetic dipoles oscillating with the same phase [1, 4, 5, 6]. As a result, nearly twice higher directivity than that of a single electric dipole has been reported. However, this directivity is still insufficient for nanophotonics applications.

2. Results and discussions

Here we reveal a way for achieving superdirectivity of antennas with a subwavelength (maximum size 0.4-0.5 λ) radiating system without using complex antenna arrays, and it is valid for a wide range of frequencies. First, we demonstrate possibility to create a superdirective optically small nanoantenna that does not require metamaterial. We consider one semiconductor nanoparticle with the permittivity $\mathrm{Re}\varepsilon = 15 - 16$ radiated by light at wavelength λ (for λ =440-460 nm this corresponds to a nanoparticle made of crystalline silicon [9]) and the radius $R_{\mathrm{S}} = 90$ nm being almost five times smaller than λ. For a perfect sphere, lower-order multipoles for both electric and magnetic fields are excited while the contribution of higher-order modes is negligible [4, 5, 6, 8]. However, making a small notch in the spherical particle breaks the symmetry allowing the excitation of higher-order multipole moments of the sphere. This is achieved by placing a nanoemitter (e.g. a quantum dot) within a small notch created on the sphere surface, as shown in Fig. 1A. The notch in our example has the shape of a hemisphere with a radius $R_{\mathrm{n}} \ll R_{\mathrm{S}}$. The emitter can be modeled as a point-like dipole and it is shown in the figure by a red arrow. It turns out that such a small modification of the sphere would allow the efficient excitation of higher-order spherical multipole modes.

To study the problem numerically, we employ the software package CST Microwave Studio. To characterize the antenna properties we calculated the directivity D defined as:

$$D = \frac{4\pi \mathrm{Max}[p(\theta, \varphi)]}{P_{\mathrm{rad}}}, \qquad (1)$$

where $P_{\mathrm{rad}} = \int_{\Omega} p(\theta, \varphi) d\Omega$ is a total power radiated in the far field, $\mathrm{Max}[p(\theta, \varphi)]$ is the power flux density radiated in the direction of maximal flux density, θ and φ are the angles of conventional spherical system, $d\Omega$ is the elementary solid angle. Figure 1B shows the dependence of the maximum directivity D_{mav} on the position of the emitting dipole in the case of a sphere $R_{\mathrm{S}} = 90$ nm without a notch, at the wavelength $\lambda = 455$ nm (blue curve with crosses). This dependence has the maximum ($D_{\mathrm{max}} = 7.1$) when the emitter is placed inside the particle at the distance 20 nm from its surface. The analysis shows that in this case the electric field distribution inside a particle corresponds to the noticeable excitation of higher-order multipole modes. This becomes possible due to strong inhomogeneity of the external field produced by the nanoemitter. Furthermore, the excitation of higher-order multipoles can be significantly improved by making a small notch in the silicon spherical nanoparticle and placing the emitter inside that notch, as shown in Fig. 1. This modification of the nanoparticle transforms it into a resonator for high-order multipole moments. In our problem, the notch has the form of a hemisphere with the center it the dielectric nanoparticle's surface. The optimal radius of the notch is $R_{\mathrm{n}} = 40$ nm, that we find by means of numerical optimization. Red curve with circles in the Fig. 1b shows maximum of directivity corresponding to this geometry. Maximal directivity at wavelength 455 nm is $D_{\max} = 10$.

Expansion of the field into multipoles offers an illustrative description of the internal field composition for the spherical particle. This is given by a series of spherical harmonics with the coefficients $a_E(l,m)$ and $a_M(l,m)$, which characterize the electrical and magnetic multipole moments [10, 7].

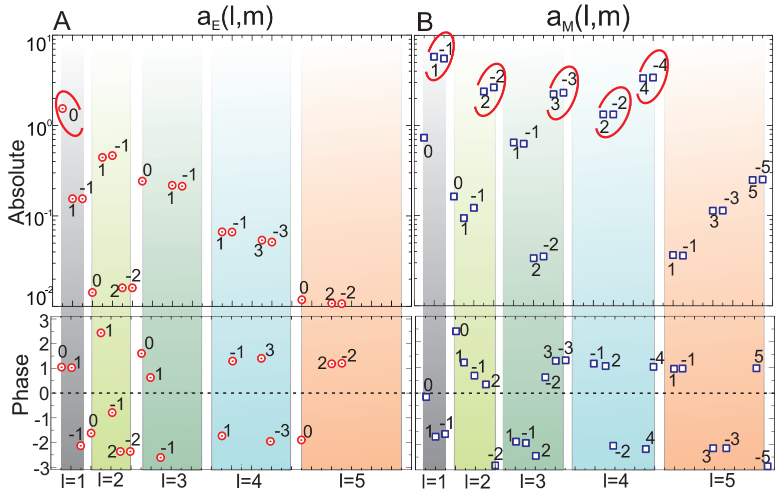

Figure 2. Absolute values and phases of (**A**) electric and (**B**) magnetic multipole moments that provide the main contribution to the radiation of all-dielectric superdirective optical nanoantenna at the wavelength 455 nm. Multipole coefficients providing the largest contribution to the antenna direction are highlighted by red circles. Particle and notch radii are equal to $R_{\rm S} = 90$ nm and $R_{\rm n} = 40$ nm, respectively.

In general, the multipole coefficients determine not only the mode structure of the internal field but also the angular distribution of the radiation. Internal field was calculated numerically with the expansion into the multipole series. The multipole moments for this case are shown in figure (Fig. 2), where we observe strong excitation of $a_E(1,0)$, $a_M(1,1)$, $a_M(1,-1)$, $a_M(2,2)$, $a_M(2,-2)$, $a_M(3,3)$, $a_M(3,-3)$, $a_M(4,2)$, $a_M(4,-2)$, $a_M(4,4)$ and $a_M(4,-4)$. These multipole moments determine the angular pattern of the antenna. All other ones give a negligible contribution. Absolute values of all magnetic moments are larger than those of the electric moments in the corresponding multipole orders, and the effective spectrum of magnetic multipoles is also broader than that of the electric moments. Thus, the operation of the antenna is mainly determined by the magnetic multipole response. Absolute values of multipole coefficients $a_M(l,\pm|m|)$ of the same order l are practically equivalent, however, the phase of these coefficients are different. Therefore, the modes with $+|m|$ and $-|m|$ form a strong anisotropy of the forward–backward directions that results in the unidirectional radiation.

We have confirmed both predicted effects studying the similar problem for the microwave range. To do this, we have scaled up the nanoantenna as above to low frequencies. Instead of Si we employ MgO-TiO_2 ceramic [5] characterized at microwaves by a dispersion-less dielectric constant 16 and dielectric loss factor of $1.12{\cdot}10^{-4}$. The results of the experimental investigations and numerical simulations of the pattern in both E- and H-planes are summarized in (Figs. 3A,B). Radiation patterns in both planes are narrow beams with a lobe angle about 35°. Experimentally obtained coefficients of the directivity in both E- and H-planes are equal to 5.9 and 8.4, respectively (theoretical predictions for them were equal, respectively, 6.8 and

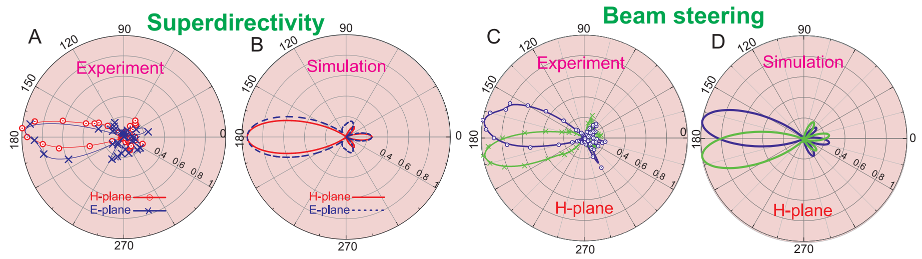

Figure 3. (color online) Experimental (**A**) and numerical (**B**) radiation patterns of the antenna in both E- and H-planes at the frequency 16.8 GHz. The crosses and circles correspond to the experimental data. Experimental (**C**) and numerical (**D**) demonstration of beam steering effect, displacement of dipole is equal 0.5 mm.

8.1). Our experimental data are in a good agreement with the numerical results except a small difference for the E plane, that can be explained by the imperfect symmetry of the emitter. Note, that the observed directivity is close to that of an all-dielectric Yagi-Uda antenna with overall size 2λ [5]. The total size of our experimental antenna is closed to $\lambda/2.5$. Thus, our experiment clearly demonstrates the superdirective effect.

Experimental and numerical demonstration of the beam steering effect are presented in (Figs. 3C,D). For the chosen geometry of antenna, displacement of source by 0.5 mm leads to a rotation of the beam about 10°. Note that the ratio of $\lambda = 18.7$ mm to value of the source displacement 0.5 mm is equal to 37. This proves that the beam steering effect observed at subwavelength displacement of source.

Acknowledgments
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