All-Dielectric Optical Nanoantennas

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Abstract

We suggest and study in detail a novel type of optical nanoantennas made of high-permittivity low-loss dielectric spheres. In addition to the electric resonances, they exhibit very strong magnetic resonances at the nanoscale. By placing a point-like dipole source near a single dielectric particle driven at the magnetic resonance results the radiation pattern similar to that of a Huygens source with the enhanced forward and vanishing backward emission. This feature can be employed in the Yagi-Uda geometry for highly efficient optical nanoantennas. We suggest the concept of optical all-dielectric antennas and verify experimentally in the microwave frequency range.

1. Introduction

The recently emerged field of optical nanoantennas is promising for its potential applications in various areas of nanotechnology [1]. The ability to redirect propagating radiation and transfer it into localized subwavelength modes at the nanoscale makes the optical nanoantennas highly desirable for efficient solar cells, biological and chemical sensing, quantum communication systems, molecular spectroscopy and, in particular, for the emission enhancement and directionality control over a broad wavelength range. We suggest [2] a novel type of optical nanoantennas made of all-dielectric elements and argue that, since the source of EM radiation is applied externally, dielectric nanoantennas can be considered as the best alternative to their metallic counterparts. First, dielectric materials exhibit low loss at the optical frequencies. Second, as was suggested earlier [3], nanoparticles made of high-permittivity dielectrics may support both electric and magnetic resonant modes. This feature may greatly expand the applicability of optical nanoantennas for, e.g. detection of magnetic dipole transitions of molecules. In our study we concentrate on nanoparticles made of silicon. The real part of the permittivity of the silicon is about 16 [4], while the imaginary part is up to two orders of magnitude smaller than that of nobel metals (silver and gold).

2. Huygens source and dielectric Yagi-Uda nanoantenna

The mentioned above properties of dielectric nanoparticles allow to realize optical Huygens source [5] consisting of a point-like electric dipole operating at the magnetic resonance of a dielectric nanosphere (Fig.1a). Such a structure exhibits high directivity with vanishing backward scattering and polarization independence, being attractive for efficient and compact designs of optical nanoantennas.

In Fig. 2a we show the dependence of the Directivity versus wavelength for a single dielectric nanoparticle excited by a electric dipole source. The inserts demonstrate 3D angular distribution of the radiated

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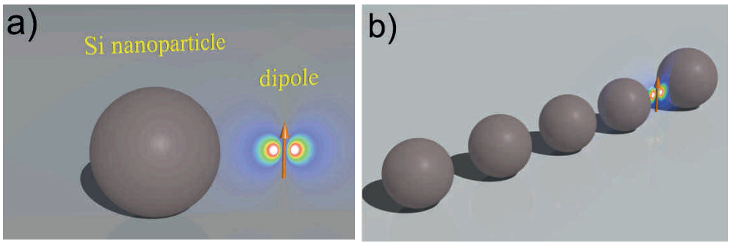

Fig. 1: Schematic view of the problem: (a) Huygens element consisting of a single silicon nanoparticle and point-like dipole source separated by a distance $G_{ds} = 90$ nm (between dipole and sphere surface). The radius of the silicon nanoparticle is $R_s = 70$ nm. (b) Dielectric optical Yagi-Uda nanoantenna, consisting of the reflector of the radius $R_r = 75$ nm, and smaller director of the radii $R_d = 70$nm. The dipole source is placed equally from the reflector and the first director surfaces at the distance G. The separation between surfaces of the neighbouring directors is also equal to G.

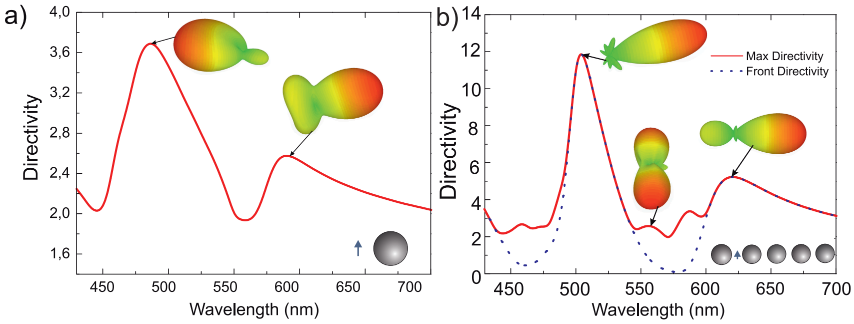

Fig. 2: (a) Dependence of the directivity D on the wavelength. (b) Directivity of the dielectric Yagi-Uda nanoantenna vs wavelength for the separation distance $G = 70$nm. Insert demonstrates 3D radiation pattern diagrams at particular wavelengths.

pattern corresponding to local maxima. One can clearly see, that in case the system radiates mostly in the forward direction at $\lambda = 590$nm, while in another case, the radiation is predominantly in the backward direction at $\lambda = 480$nm.

By adding more elements to the single silicon nanoparticle it is possible to enhance the nanoantenna performance. Next we consider the dielectric analogue of the Yagi-Uda like design, shown in Fig. 1b. It consist of four directors and one reflector. The radius of the directors and the reflector should be chosen is such a way to achieve the maximal constructive interference in the forward direction along the directors chain. In Fig. 2b we plot the directivity of the dielectric Yagi-Uda nanoantenna versus wavelength with the separation distance $G = 70$nm. The strong maximum is obtained at $\lambda = 500$nm. The main lobe is extremely narrow with the beamwidth about 40° and the backscattering is negligible, as it can be seen from the corresponding insert.

2. Experimental verification of the concept of all-dielectric nanoantennas

We scale the dimensions and provide the first experimental verification of the concept of all-dielectric nanoantennas. Figures 3(a,b) show the photographs of the fabricated all-dielectric Yagi-Uda antenna. To mimic the silicon spheres at the microwave frequency range, we employ MgO-TiO_2 ceramic which is characterized by dielectric constant of 16 and dielectric loss factor of (1.12-1.17)10^{-4} measured at 9-12 GHz frequency range. As a source, we use a half-wavelength vibrator. We study experimentally both the radiation pattern and directivity of the antenna.

The antenna radiation patterns in the far field (at the distance $\simeq 3$ m, $\simeq 100\lambda$) are measured in an anechoic

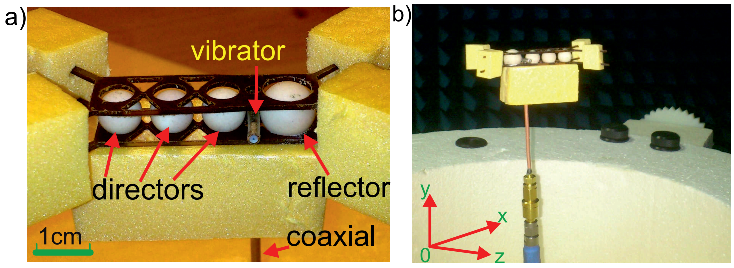

Fig. 3: Photographs of the all-dielectric Yagi-Uda microwave antenna. (a) Detailed view of the antenna placed in a holder. (b) Antenna placed in an anechoic chamber; the coordinate z is directed along the vibrator axis; the coordinate y is directed along the antenna axis.

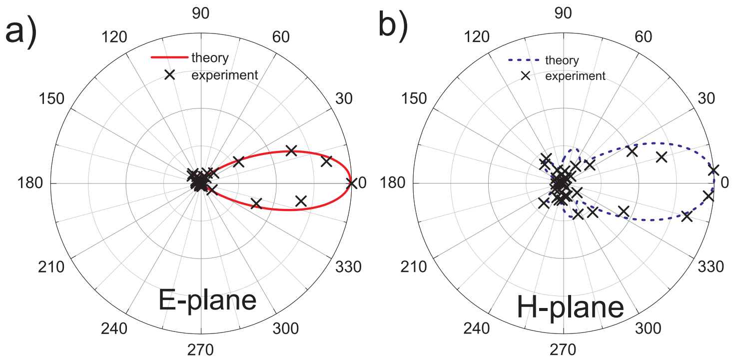

Fig. 4: Radiation pattern of the antenna in (a) E-plane and (b) H-plane at the frequency 10.7 GHz. Solid lines show the results of numerical simulations in CST; the crosses correspond to the experimental data.

chamber by a horn antenna and rotating table. The measured radiation patterns of the antenna in E- and H-planes at the frequency 10.7 GHz are shown in Fig. 4. The measured characteristics agree very well with the numerical results.

4. Conclusion

In this work we suggested and verified experimentally new type of optical nanoantennas made of dielectric nanoparticles. It was demonstrated that even single silicon nanoparticle can exhibits high directivity. Being excited by an electric dipole source at the magnetic resonance its radiation pattern is similar to that of the Huygens element. This is the simplest, most efficient, and most compact example of optical nanoantennas. We demonstrated experimentally that the microwave antennas composed of high-permittivity spheres provide the narrow radiation pattern of about 40°, as predicted by numerical calculations. This may allow to create a new generation of optical nanoantennas.

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