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In this paper, we propose a new kind of nanoantenna for effective illumination of parabolic surfaces, constituting of a silicon cylinder acting as a reflector and dipole source as an emitter. Tailored parameters of the nanoantenna ensure specific radiation pattern with broad main lobe and strongly suppressed side lobes that in the E-plane of the dipole is quite similar to the ideal "Π" configuration, necessary for an as uniform as possible illumination of parabolic surfaces. This above radiation pattern is mostly due to the properly designed dielectric inclusion in the reflector that, therefore, is free of any losses. Consequently, we study how varying the antenna parameters affects the radiation pattern. Results of our numerical simulations are compared with already existing ones and highlight the principal features that provide the desired effect. Furthermore, due to the simple geometry of the inclusions, the considered nanoantenna, required in application such as nanoreflector antennas and/or nanophotonic devices, exhibits advantages in manufacturing processes with respect to already proposed solutions.

Key words: all-dielectric antenna, radiation pattern, parabolic reflector, gas discharge, electron runaway, ionization, particle method.
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1 Introduction

Nanoantennas are now widely researched devices for application in nanophotonics, plasmonics and nanooptics [1-13]. Firstly, the idea of nanoantenna was proposed in 1928 by E. Synge, who exploited colloidal gold particles both for localizing optical radiation and for overcoming the diffraction limits [14]. Furthermore, J. Wessel applied these particles for nanoscale antennas [15]. In contrast with their classical counterparts, nanoantennas can be fabricated from not only metallic and dielectric materials; molecules (or even atoms), luminescent and fluorescent cells of viruses and bacteria, quantum dots and wires can be used as nanoantennas. Therefore, nanoantennas do not require such complex volumetric design as classical antennas, so their nanoscale analogues gains in fabrication [16-29].

On the other hand, nanoantennas are of great interest for their ability to control electromagnetic field patterns in nanoscale media. Due to small size compared to field wavelength, they are equally important as elements for lensing, waveguides and scatterers that are traditionally used for the electromagnetic field manipulation in a wide optical range [30-34].

The principle of nanoantennas, as well as classical antennas, is determined by the effective conversion of the electromagnetic field into localized energy and vice versa. Usually, a nanoantenna is fed by a dipole source with dimensions much smaller than its operating wavelength. The radiating nanoantenna is supplied (supported) by a concentrated dipole field that significantly enhances and directs its radiation power. This dipole radiation zone is divided into far-field and near-field zones. Since electric and magnetic fields oscillate in phase in far-field zone, active electromagnetic energy is radially transmitted far from the antenna. On the other hand, field vectors oscillations in near-field zone features mainly quadrature of radiation power and the Poynting vector possesses imaginary value, so the reactive electromagnetic energy is conserved close to the source. In the region between near-field and far-field zones, the phase difference between electric and magnetic field varies smoothly from $\pi/2$ to zero with distance, leading to destructive interference between them. Nevertheless, this phenomenon can be overcame by specially designed and placed subwavelength resonator that provides (i) in-phase oscillations of electric and magnetic fields in near-field and (ii) efficient re-radiation to the far-field zone.

While the approach of classical antennas is based on the conversion of electromagnetic wave to the localized field or vice versa, the interaction of light-matter between the incident wave and nanoantenna is of a different nature [7, 9, 11-13, 31, 35]. Indeed, an impinging wave interacts with the nanoantenna and causes near-field resonances on plasmonic and all-dielectric subwavelength particles called plasmonic and Mie-resonances, respectively. Therefore, these nanoscale effects determine the directivity and radiation control: the forward/backward scattering of nanoantennas is eliminated by fulfillment of the Kerker conditions; the radiation pattern is controlled by the manipulation of the nanoantenna geometry [35].

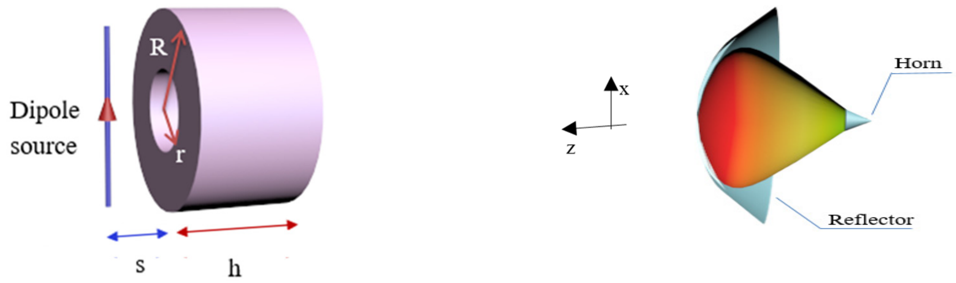
Moreover, radiation pattern is conditioned by its application: for communication between distant emitters, a narrow concentration of the transferring energy beam is required [3, 5-9, 33-35]. On the other hand, for a number of tasks, a weak and particularly shaped one-sided directivity is needed [36].

Notably, the linearity of Maxwell equations allows transferring of known elegant solutions for microwave antennas to novel nanoantennas [7]. Generally, microwave reflector antenna consists of feed and parabolic/spherical reflector and it can be exploited for uniform illumination of enhanced directivity of such surfaces as collimator mirrors [37]. For the sake of effective irradiation, the feed should satisfy the following main criterion: it should provide constant field distribution in the center of the reflector that abruptly decreases to minimum values at its edges to suppress diffraction. Usually, horn and waveguide feeds are used for irradiation of mirror microwave antennas. They provide the radiation pattern with enhanced main lobe and substantially suppressed side lobes resembling an attenuating cosine curve. However, the ideal radiation pattern looks like Greek letter “П”, with smooth main lobe and suppressed side lobes that perfectly shapes the surface of a parabolic reflector (Figure 1a). Thus, reflector antenna principle can be transferred from microwave to the optical frequencies and applied for nanoscale photodetection, light emission and sensing, nanoimaging and others [1, 2, 4, 13, 14].

2 The structure of the system

Here we describe the proposed nanoantenna consisting of the feed based on dipole source with all-dielectric hollow cylindrical nanoparticle (Figure 1a) acting as a reflector. Such nanoantenna is awaited to provide effective almost uniform irradiation by means of smooth forward radiation with significantly suppressed side lobes (see Figure 1b). Besides the awaited radiation pattern, this structure does not require complex geometry and fabrication, since the feed is made from the all-dielectric material that is characterized by strongly suppressed dissipative losses.

Here, we aim to extend the application of nanoreflectors for illumination purposes. The feed pattern should provide an almost uniform main lobe that abruptly attenuates on the reflector edge so that resembles the ideal “П” configuration (Figure 1b). The single dipole (oriented along the x direction, in Figure 1a) source causes a uniform omnidirectional radiation pattern (Figure 2b red curve), that illuminates the entire parabolic reflector including edges causing high diffraction and spillover. In combination here with a dielectric hollow cylinder, we can manipulate the radiation from the dipole source and adjust it in such a way to get the desired “П” radiation pattern (Figure 2b black curve). Namely, hollow cylinder significantly changes the radiation pattern: instead of a convex radiation pattern from the whole cylinder (Figure 2b blue curve), the hole leads to a straightened main lobe to the “П”-shape due to the deceleration of the wave propagation in the hole and in the walls of the dielectric cylinder. In both cases, the cylinder acts as a reflector (similarly to a Yagi-Uda configuration), that will increase the radiation in the +z direction in the detriment of that in the –z direction. At the same time, this cylindrical inclusion provides suppressed side lobes, so that we approach the ideal "Π" configuration.



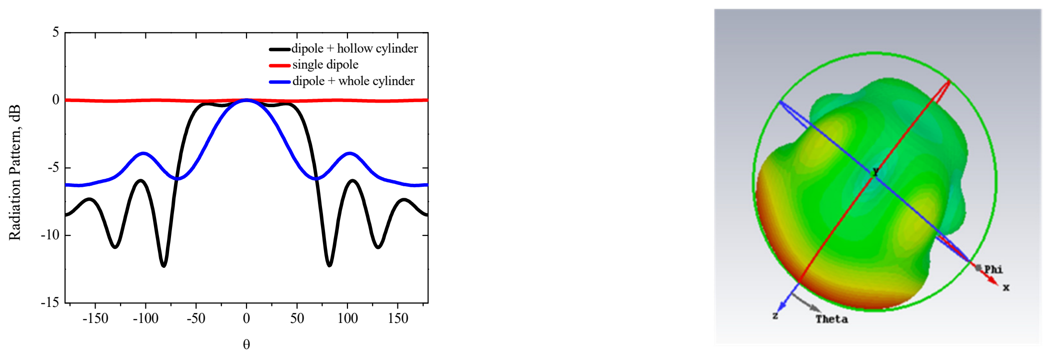
(a) (b)

Figure 1 – Illustration of proposed nanoantenna consisting of dipole source and dielectric cylinder (a) and of ideal radiation pattern, repeating the shape of the reflector (b). The inner and outer radii are r=1.2 um and R=2 um, respectively, the height is h=2.4 um. The distance between the dipole and the top of the cylinder is s=0.12 um.

We consider the dielectric hollow cylinder with relative dielectric permittivity ε_r=15 which is placed in vacuum. The cylinder has the following parameters: inner and outer radii are r=1.2 um and R=2 um, respectively, the height is h=2.4 um. The electric dipole located in the front of the cylinder at a distance s=0.12 um perpendicular to the axis of symmetry of the cylinder. The electromagnetic properties of the proposed structure have been calculated by means of the commercial solver CST Microwave Studio using open boundary conditions.

3 Results of calculations and their discussion

We study the far-field properties in the infrared (IR) frequency range. The far-field pattern with a broad main lobe and strongly suppressed side lobes corresponds to f=65 THz. Therefore, the far-field map indicates that the radiation of the nanoantenna perfectly replicates the shape of a convex reflector and, therefore, possesses sufficiently low side and backward lobes (Figure 2). The normalized radiation pattern in Cartesian coordinates in the x0z plane strongly resembles the ideal "Π"-shaped configuration of the main lobe. The main lobe width is ±50°, meanwhile side lobes are narrowed (50°) and suppressed down to -7 dB (Figure 2a). Moreover, we compare the nanoantenna radiation pattern with the characteristics of a dipole source (red curve) and a whole cylinder (blue curve). As expected, the dipole source has the same intensity at all angles. On the other hand, the directional pattern of the entire cylinder loaded dipole has the cosine shape of the main lobe (Figure 2a blue curve).



(a) (b)

Figure 2 – Radiation pattern versus angle of the nanoantenna in (a) Cartesian coordinate system (angles are in degree) and (b) 3D diagram. The blue curve stands for dipole source radiation, red curve for whole cylinder and black curve for hollow cylinder radiation at f=65 THz.

The parameters of cylinder are responsible for the shape, intensity and width of the main/side lobes. Particularly, the inner radius strongly affects forward scattering, resulting in non-uniform main lobe and rather high values of side lobes. Smaller inner radii (r=1 um, 1.1 um) lead to an increase of side and backward lobes, while larger radii (r=1.3 um, 1.4 um) give rise to a convex main lobe with less affected side lobes (Figure 3a). Furthermore, the dielectric permittivity ε of the cylinder determines the amount of displacement currents induced inside the cylinder that completely changes the radiation pattern. Gradual increase of the permittivity changes concave main lobe (ε_r=13) to a sharply convex main lobe (ε_r=14, 16, 17) with high side lobes (Figure 3b). The manipulation of the height h of the cylinder broadens the main lobe and drastically changes its shape from deeply concave to sharply convex and increases the intensity of the side lobes (Figure 3c).

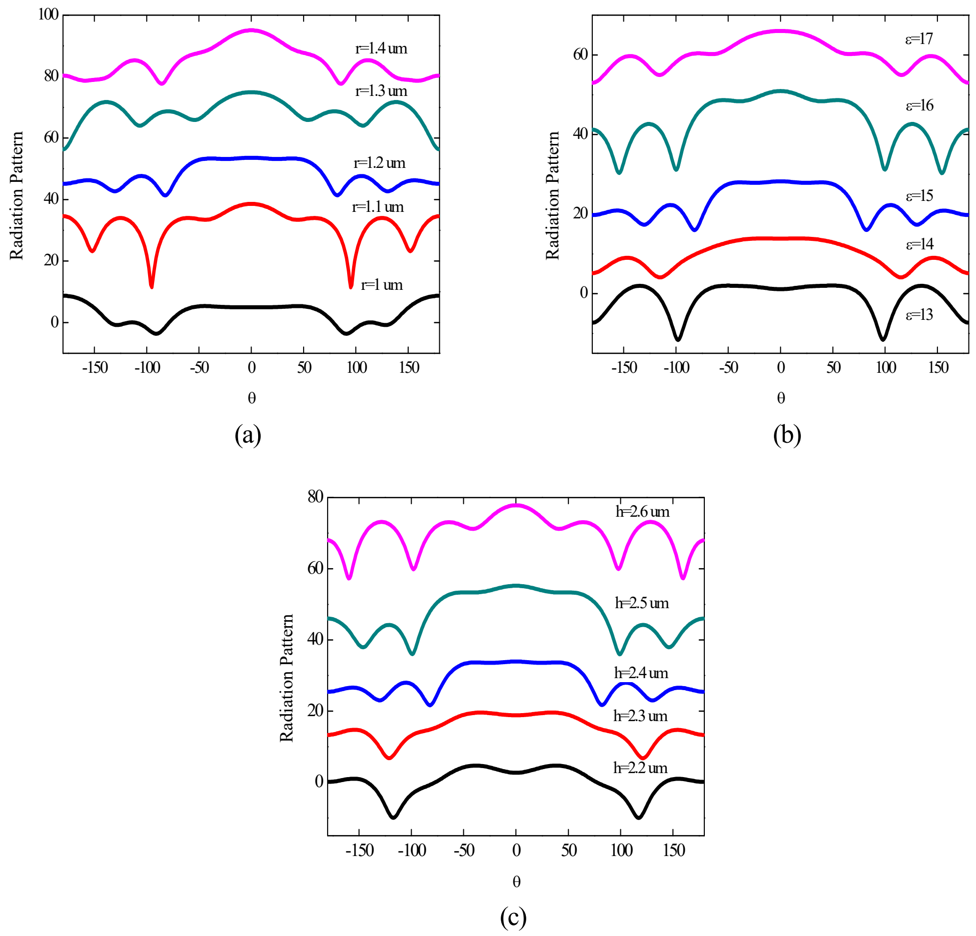


Figure 3 – Radiation pattern for (a) different inner radii r of dielectric cylinder for outer radius R=2 um and ε_r=15; (b) different dielectric permittivity ε of dielectric cylinder for fixed radii r=1.2 um and R=2um; (c) different height h of dielectric cylinder for fixed radii r=1.2 um and R=2um and ε_r=15. Values on the vertical axis for quantification purpose, allowing a numerical comparing of the radiation patterns.

We should also mention other techniques regarding the generation of a uniform field distribution. Yin et al. demonstrated one possible solution for uniform illumination of nanoscale parabolic/spherical reflectors due to the surface plasmon polaritons (SPP) excitation [38]. This configuration demands the fabrication of nanometric holes with a metal strip waveguide for SPP excitation. The constructive interference of SPP focuses on a highly concentrated SPP beam in the center of the semicircle. This metal-dielectric hybrid structure is promising for subwavelength focusing and guiding, but it possesses both complicated fabrication process and dissipative losses. Another solution is a Cassegrain-type curved reflecting mirror [39], widely known for high focusing and imaging functionalities; however, this type is bulky and not expandable. The complex geometry requires a two-level mirror system that possesses high chromatic aberrations and does not provide high efficiency. On the other hand, we propose the nanoantenna for uniform illumination that, in the first instance, is of a simple design and does not require complex fabrication technique, that is crucial for nanoscale devices. Moreover, the considered dielectric inclusion benefits of low dissipative losses and this nanoantenna can be scaled for a wide range of frequencies.

4 Conclusions

In this paper, we demonstrated a new all-dielectric nanoantenna for efficient irradiation of parabolic reflectors that, therefore, possesses low dissipative losses. The parameters of the structure are properly chosen in order to obtain efficient radiation pattern resembling the Greek letter "Π". The obtained numerical results show wide forward scattering with suppressed side and back scattering. The inherent low dissipative losses of this nanoantenna potentiate its application in more anticipated optical frequency range.

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