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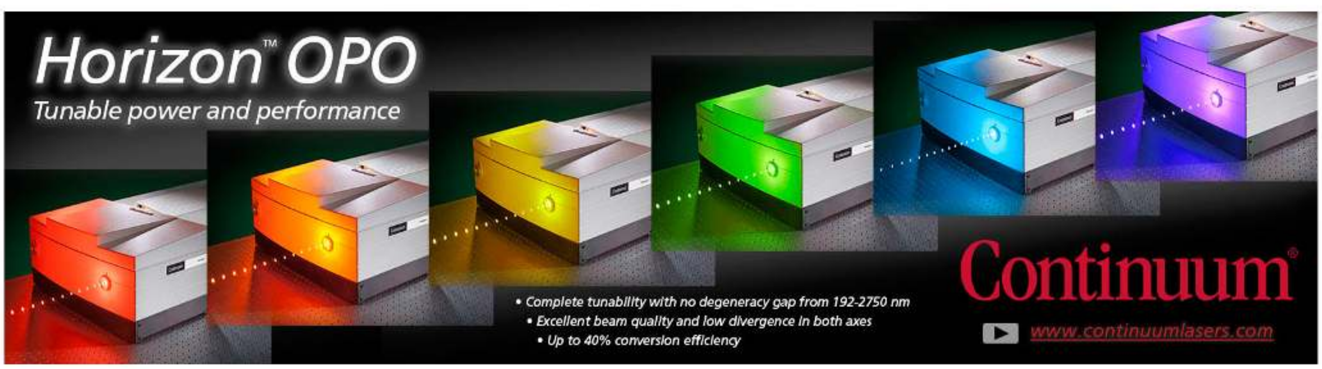

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Experimental verification of the concept of all-dielectric nanoantennas

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Being motivated by the recent theoretical proposal of nanoantennas based on high-permittivity dielectric spheres [A. E. Krasnok *et al.*, JETP Lett. **94**, 22113 (2011)], we suggest and verify experimentally the concept of all-dielectric antennas in the microwave frequency range. In addition to the electric resonance, each sphere exhibits a very strong magnetic resonance, resulting in a narrow radiation pattern and overall high directivity of such antennas. We find an excellent agreement between the experimental data and numerical results and verify directly high-performance characteristics of such all-dielectric antennas potentially scalable to the nanoscale and operation at the optical frequency range. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4719209]

One of the important problems of nanophotonics is the connection of nanoscale elements with optical circuitry at deeply subwavelength scales. This problem can be solved by employing the concept of *optical nanoantennas*. Nanoantennas are optical devices allowing to redirect the propagation radiation and transfer its power into strongly localized subwavelength modes.[1–18] For an effective operation, an optical nanoantenna consisting of subwavelength elements should provide a narrow radiation pattern, low level of dissipation losses, and demonstrate a high directivity.

The experimentally fabricated optical nanoantennas are usually made of subwavelength metallic elements, and such *plasmonic nanoantennas* mimic directly the classical analogue of the Yagi-Uda radio-frequency antenna design.[3,6,8,9,12,13,16,17] Similar to the radio-frequency design principle, a nanoantenna consists of an actively driven element called *feed* surrounded by passive elements. These elements are usually of two types: a *reflector* and an array of equally spaced *directors* (e.g., see Fig. 1). The feeding element is designed to be at resonance with the emitter, while the reflector and directors are chosen to be off the resonance.

However, it was demonstrated that plasmonic nanoantennas based on metallic nanoparticles can satisfy only a part of the required demands. In particular, such nanoantennas exhibit high directivity due to the excitation of localized subwavelength plasmons, but they experience high dissipation losses which drastically increase when the distance between metallic nanoparticles becomes smaller. Moreover, there exists a technological limitation concerning to the metals suitable for practical applications, so that in general only gold and silver are used.

Recently, Krasnok *et al.*[19] suggested optical nanoantennas based on an array of all-dielectric spheres. In addition to the electric resonance, each high-permittivity sphere exhibits a very strong magnetic resonance, and this property results in a narrow radiation pattern and overall high directivity of such all-dielectric nanoantennas.

Being motivated by this theoretical proposal, in this letter, we scale the dimensions and provide the first experimental verification of the concept of all-dielectric nanoantennas by fabricating and characterizing Yagi-Uda microwave antennas based on high-permittivity dielectric spheres. We find an excellent agreement between the experimental data and numerical results and verify experimentally high directivity and narrow radiation pattern of such antennas.

The operational principle of all-dielectric optical Yagi-Uda nanoantennas made of dielectric nanoparticles with high permittivity is based on the Mie theory.[20] It has been shown that there exists a range of wavelengths where a single nanoparticle (with the radius smaller then the wavelength) made of silicon (Si) being excited by an electric dipole source near the magnetic resonance radiates with the radiation pattern similar to that of a Huygens source.[19] It is also possible to introduce dielectric and magnetic polarisabilities for a spherical nanoparticle in the dipole approximation as:

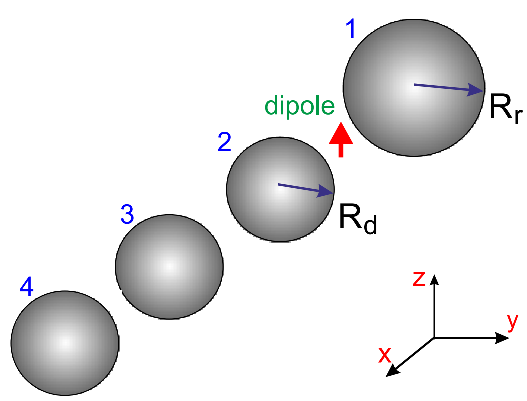

FIG. 1. Schematic of an all-dielectric Yagi-Uda nanoantenna composed of high-permittivity dielectric spheres. The antenna consists of a reflector (sphere 1) and three directors (spheres 2 to 4). A dipole source is placed equally from the reflector (sphere 1) and first director (sphere 2).

$$\alpha^e = \frac{6\pi i}{k^3} a_1, \quad \alpha^m = \frac{6\pi i}{k^3} b_1, \tag{1}$$

where k is the wavenumber in the free space, a_1 and b_1 are the Mie dipole scattering coefficients.[21]

A schematic view of the optical all-dielectric Yagi-Uda nanoantenna is shown in Fig. 1. The antenna consists of a larger dielectric sphere and three smaller dielectric spheres, and it is exited by a dipole source. The larger dielectric sphere (sphere 1) is the reflector which provides destructive interference to suppress the back and minor lobes of the radiation pattern. The three smaller dielectric spheres (spheres 2 to 4) play the role of the directors. They are normally designed to add up in phase in the forward direction canceling radiation in the backward direction. Thus, the number of the directors defines the antenna's directivity and the half-power beam-widths. The larger the number of the directors, the higher is its directivity. At the optical frequencies, a quantum dot or molecule can be considered as a dipole source. There exist some technological problems to reproduce an object of the nanometer size with a high accuracy. We scale the dimensions of the proposed optical all-dielectric Yagi-Uda nanoantenna to the microwave frequency range keeping all the material parameters in order to study the microwave analog of the nanoantenna experimentally.

We use the design of the Yagi-Uda antenna shown in Fig. 1. At the optical frequencies, the dielectric spheres are made of silicon which has the dielectric constant $\varepsilon = 16$.[22] 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.[23] As a source, we use a half-wavelength vibrator. We study experimentally both the radiation pattern and directivity of the antenna.

Any antenna is characterized by the total directivity which can be defined as:

$$D = \frac{4\pi \mathrm{Max}[p(\theta,\varphi)]}{\int_0^{2\pi}\int_0^{\pi} p(\theta,\varphi) d\Omega}, \tag{2}$$

where $p(\theta,\varphi)$ is the radiation pattern, the double integration in the denominator is the total power P_{rad} radiated in the far field, $\mathrm{Max}[p(\theta,\varphi)]$ is the power radiated in the direction of the main lobe, θ and φ are the conventional spherical angels, and $d\Omega$ is the element of a solid angle. This equation is normalized to 4π. Sometimes it is not possible to determine the value of the total directivity experimentally due to difficulties to measure the total radiated power P_{rad}. In this case, it is convenient to use directivity in the planes where electric field $\mathbf{E}$ and magnetic field $\mathbf{H}$ oscillate in the far field. For our coordinates, the directivity in the evaluation plane (E-plane) and the azimuthal plane (H-plane) can be expressed as:

$$D_E = \left.\frac{2\pi \mathrm{Max}[p(\theta)]}{\int_0^{2\pi} p(\theta) d\theta}\right|_{\varphi=0}, \quad D_H = \left.\frac{2\pi \mathrm{Max}[p(\varphi)]}{\int_0^{2\pi} p(\varphi) d\varphi}\right|_{\theta=\pi/2}. \tag{3}$$

Equations (3) are multiplied by 2π because the integration in the denominator is performed only for one coordinate while the second coordinate is fixed.

To estimate the performance of the all-dielectric Yagi-Uda antenna at microwaves, first we simulate numerically the antenna's response by employing the CST MICROWAVE STUDIO. We set the radius of the reflector (sphere 1) equals to $R_r = 5$ mm. The frequencies of the electric and magnetic Mie resonances of the sphere calculated with the help of Eq. (1) are 10.2 GHz and 7 GHz, respectively. The radius of the directors is $R_d = 4$ mm. In this case, the frequencies of the electric and magnetic Mie resonances are 12.5 GHz and 9 GHz, respectively. As a source, we model a half-wavelength vibrator with the total length of $L_v = 19.8$ mm and diameter of $D_v = 2.2$ mm. In numerical simulations, we adjust the distances between the reflector, directors, and vibrator. We achieve an effective suppression of the back and minor lobes, and the narrow major lobe (of about 40°) of the antenna when the distance between the director's surface as well as the distance between vibrator center and the first director surface are 1.5 mm; the distance between the surface of the reflector and vibrator centre is 1.1 mm. The numerically simulated radiation pattern in E- and H-planes is presented in Fig. 2 at the center frequency 10.7 GHz. The

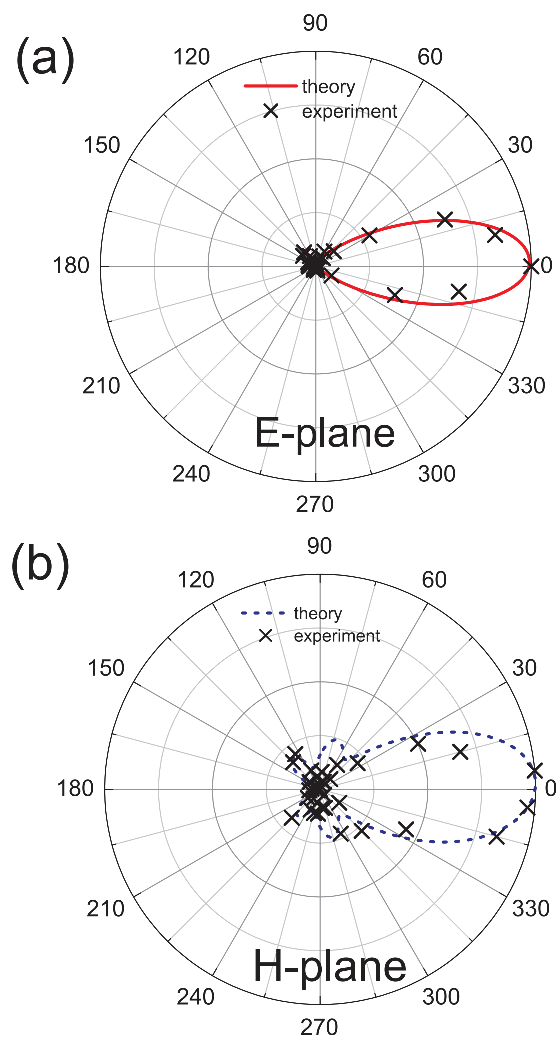

FIG. 2. Radiation pattern of the antenna in (a) E-plane and (b) H-plane at the frequency 10.7 GHz. Solid lines show the results of numerical simulations in CST; the crosses correspond to the experimental data.

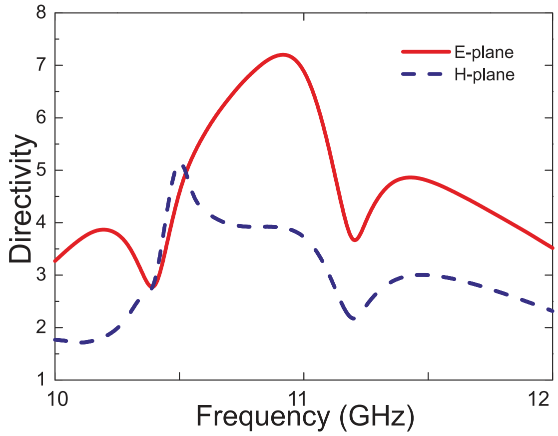

FIG. 3. Directivity of the all-dielectric Yagi-Uda antenna in E and H planes obtained from the CST numerical simulations.

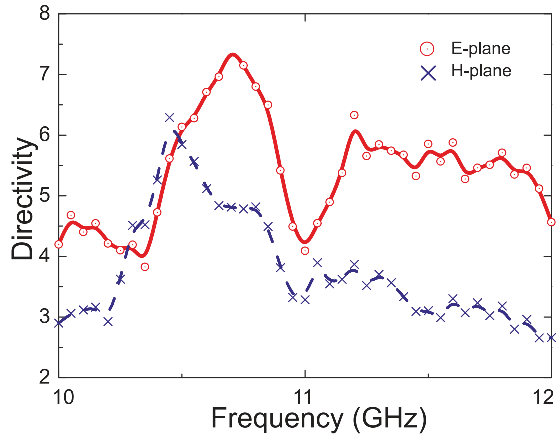

FIG. 5. Experimentally measured antenna's directivity in both E- and H-planes [cf. Fig. 3]. The curves connect the experimental points as a guide to the eye.

antenna directivity in E- and H-planes calculated with the help of Eq. (3) is presented in Fig. 3. The high directivity of the antenna is achieved at the center frequency.

Figures 4(a) and 4(b) show the photographs of the fabricated all-dielectric Yagi-Uda antenna. The reflector and directors are made of MgO-TiO_2 ceramic with accuracy of ± 0.05 mm. To fasten together the elements of the antenna and vibrator, we use a special holder made of a thin dielectric substrate [being shown in Fig. 4(a)]. Styrofoam material with the dielectric permittivity of 1 is used to fix the antenna in the azimuthal-rotation unit [see Fig. 4(b)]. To feed the vibrator, we employ a coaxial cable that is connected to an Agilent PNA E8362C vector network analyzer.

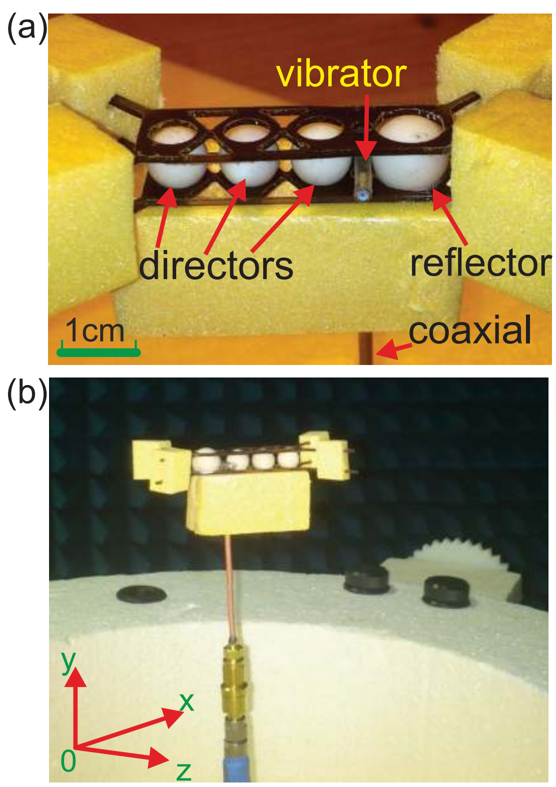

FIG. 4. Photographs of the all-dielectric Yagi-Uda microwave antenna. (a) Detailed view of the antenna placed in a holder. (b) Antenna placed in an anechoic chamber; the coordinate z is directed along the vibrator axis; the coordinate y is directed along the antenna axis.

The antenna radiation patterns in the far field (at the distance $\simeq 3$ m, $\simeq 100\,\lambda$) are measured in an anechoic 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. 2. The measured characteristics agree very well with the numerical results. A small disagreement can be explained by the presence of the antenna holder which influence was not taken into account in our numerical simulations.

To extract the antenna directivity in the E- and H-planes from the experimental data, we measure the radiation pattern by the antenna in the frequency range from 10 GHz to 12 GHz with a step of 50 MHz. Then, by employing Eq. (3) we calculate the directivity at each frequency. The results are presented in Fig. 5. We observe excellent agreement between numerical results of Fig. 3 and measured experimental data. However, we notice a small frequency shift of the measured directivity in comparison with the numerical results. These discrepancies can be explained by the effect of the antenna holders in the experiment, not included into the numerical simulation.

In conclusion, we have verified experimentally the concept of all-dielectric nanoantennas in the microwave frequency range. We have demonstrated experimentally that the microwave antennas composed of high-permittivity spheres provide the narrow radiation pattern of about 40° and high directivity in both E- and H-planes, as predicted by numerical calculations. We believe that our results support the concept of all-dielectric Yagi-Uda antennas, which can be verified subsequently in the optical frequency range. This may allow to create a new generation of optical nanoantennas.

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