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Publication date
2023

Document Version
Final published version

Published in
Proceedings of the The 13th International Conference on Metamaterials, Photonic Crystals and Plasmonics

META 2023 Paris - France

The 13th International Conference on Metamaterials, Photonic Crystals and Plasmonics

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Directional scattering by composite SiO2/Au nanoparticles

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Abstract: We show that composite nanoparticles can be designed to scatter light into a desired direction. By choosing the materials of the nanoparticle carefully, the phase of the scattered light by the different components can be controlled. This leads to constructive interference is certain directions and destructive interference in others, resulting in directional scattering obtainable for a large bandwidth. FEM simulations were used to validate the theory. Furthermore, SiO2/Au nanoparticles were fabricated and measured confirming the directional scattering.

Introduction

Most studies towards scattering by nanoparticles have focused on particles made up of a single material, where the scattering is determined by multipole resonances[1]. Combining particles of different materials allows for more degrees of freedom, which has been demonstrated for dimer and trimer structures[2,3]. However, the directional scattering by these configurations is determined by interference between their different components, acting as spatially separated point sources. Therefore, the direction of the scattered field is highly dependent on the wavelength of the light and the distance between the point sources. Thus, broadband light scattering where the scatter pattern remains constant is hard to attain. Composite nanoparticles (CNPs) could be a solution for this, as the materials are not separated.

Approach

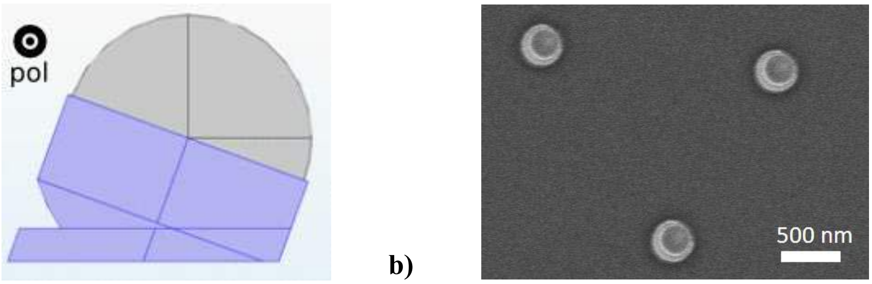
Let us consider a linearly polarized plane wave traveling in the x-direction incident on a CNP, which is inside a homogeneous medium with permittivity ε_{med}. For now we will assume that the contrast of the particle is very low compared to the medium. In this case, we can use the Born approximation in the Lipmann-Schwinger equation to calculate the scattered field. Using a spherical coordinate system, with polar angle θ (from the z-axis) and azimuthal angle φ (from the x-axis) and some algebraic steps we get the following expression for the field scattered in the forward direction:

$$\overline{E}^{sc}(r,0,\pi/2) = \overline{E}_0 \frac{k^2 e^{ikr}}{4\pi r}\left[\left(\varepsilon_{\Omega_1} - \varepsilon_{med}\right)\int_{\Omega_1} d^3 r_0 + \left(\varepsilon_{\Omega_2} - \varepsilon_{med}\right)\int_{\Omega_2} d^3 r_0\right]. \quad (1)$$

Here, k is the wavenumber in the medium, ε the permittivity, E the electric field and Ω_1 and Ω_2 the volumes occupied by the different materials. From Equation 1, we see that the scattered field is determined by the volume of the materials and their permittivity. By choosing different sizes and materials, the magnitude of the scattered field can be controlled.

To investigate whether this relation holds beyond the Born approximation, a SiO2/Au CNP in air was simulated using the FEM software COMSOL. To make fabrication possible, a geometry was chosen of a spherical SiO_2 particle (with a diameter of 300 nm) with Au attached to its side (Figure 1a). The calculated scattered light intensity for incident light with a wavelength of 633 nm is shown in Figure 2a.

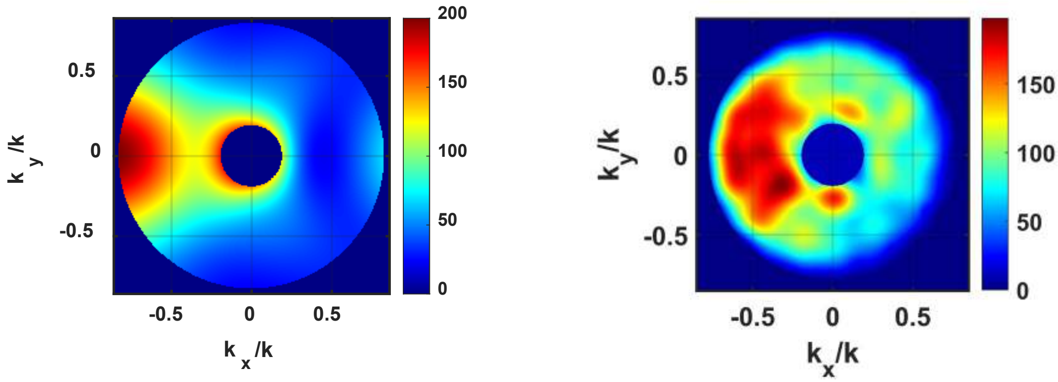
Samples of SiO2/Au CNPs of the same geometry were fabricated. A solution of colloid SiO2 nanospheres were deposited onto a glass wafer. Next, the sample was sputtercoated with a layer of 40 nm Au. Finally, most of the gold was removed by ion beam etching at an angle of 20 degrees, so that only the Au in the shadow of the nanoparticle remained. The samples were inspected using a SEM, the result can be seen in Figure 1b.



a) **b)**

Figure 1: a) Geometry of the SiO2/Au CNP in the simulation. The blue part is made of Au and the grey part is made out of SiO2. The polarization of the incident light used for simulations and measurements is also indicated; **b)** SEM micrograph of three fabricated SiO2/Au CNPs

The scattering of the manufactured CNPs was measured using a transmission Fourier microscope setup using a HeNe laser as a light source with a *y*-polarization. Figure 2 shows the simulated and the measured scattering intensity produced by a single CNP in the Fourier plane. It can be seen that most of the light is scattered to the left of the particle and that the measurement corresponds to what is expected from the simulation.



a) **b)**

Figure 2. Scattered light intensity in the Fourier plane by a SiO2/Au CNP on a glass substrate with incident y-polarized light: **a)** simulated using a FEM software; **b)** experimentally measured. (arbitrary units)

Conclusion

We have shown that directional scattering can be achieved by CNPs with the right material combinations for their components. Theory and FEM simulations show that the phase differences of the scattered field caused by the material properties of the CNP are the source of the directional scattering. Subsequent experimental measurements confirm the directional scattering found by the FEM software.

Acknowledgements

We acknowledge support by NWO-TTW Perspectief program (P15-36) "Free-form scattering optics".

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