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Achieving directional scattering through a phase difference in composite nanoparticles

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Abstract: We show that the scattering of light by a composite nanoparticle leads to directional scattering through the phase difference between the light scattered by each of the materials. The resulting scatter pattern is experimentally verified.

1. Introduction

Over the last decade, many studies have been done towards the scattering by nanoparticles. Most studies have focused on particles made up of a single material. Combining particles of different materials allows for more degrees of freedom, which has been demonstrated for dimer and trimer structures [1–3]. However, the directional scattering by these configurations is determined by interference between their different components, which is also very dependent on the wavelength of the light. Therefore, broadband light scattering where the scatter pattern remains constant is hard to attain. Composite nanoparticles (CNPs) could be a solution for this.

2. Approach

Let us consider a CNP inside of a homogeneous medium. We will denote the space occupied by this particle as Ω. The electric field affiliated with the light incident on the particle is given by $\boldsymbol{E}^{inc}(\boldsymbol{r})$. The scattered field can then be written as [4]

$$\boldsymbol{E}^{sc}(\boldsymbol{r}) = k^2 \int_{\Omega} G^E(\boldsymbol{r},\boldsymbol{r_0})(\varepsilon(\boldsymbol{r_0}) - \varepsilon_{med})\boldsymbol{E}(\boldsymbol{r_0})d^3r_0. \tag{1}$$

Here, k is the wavenumber in the medium, ε the relative permittivity, $\boldsymbol{E}$ the electric field vector, and $G^E(\boldsymbol{r},\boldsymbol{r_0})$ the Green's function.

Now let us consider a particle made up of two different materials. Therefore, we will split the particle up in two different components: Ω_1 and Ω_2 (where ε is constant). The resulting equation is hard to solve, so in order to further our argument, we will assume the particle has a very low contrast compared to the medium. Furthermore, we will consider an incident field which is a plane wave traveling in the x-direction with magnitude and polarization $\boldsymbol{E_0}$ in the yz-plane. Through some algebraic steps, we come to the following expression for the scattered light travelling in the forward direction:

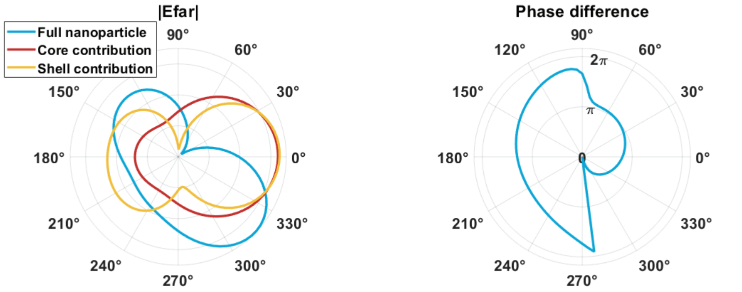
$$\boldsymbol{E}^{sc}(r,0,\pi/2) = \boldsymbol{E_0}(\varepsilon_{\Omega_1} - \varepsilon_{med})\frac{k^2e^{ikr}}{4\pi r}\int_{\Omega_1} d^3r_0 + \boldsymbol{E_0}(\varepsilon_{\Omega_2} - \varepsilon_{med})\frac{k^2e^{ikr}}{4\pi r}\int_{\Omega_2} d^3r_0. \tag{2}$$

The resulting integrals are simply the size of the different volumes that each component of the CNP occupies. Therefore, the phase difference between the scattered fields of the two components of the CNP is governed by the $(\varepsilon_{\Omega_{1,2}} - \varepsilon_{med})$ terms. A phase difference of π can be achieved by either choosing the component materials so that the electric permittivity of the medium is in between that of the different components in the lossless case, or by using materials with complex permittivity.

In order to achieve asymmetry in the scatter pattern produced by a CNP, the CNP itself must also be asymmetric. Therefore, we have chosen to simulate the scattering created by a core-semishell CNP using a FEM software (COMSOL). To introduce the phase difference between the core and the semishell, a dielectric was chosen for the core (SiO_2), a metal for the semishell (Au) and the medium was chosen to be air. After solving for the electric field, Equation 2 was used to determine the scatter pattern for the core and semishell separately, as well as for the entire CNP. These results are shown in Figure 1.

From the figure, it can be seen that the directionality of the scattering is due to the destructive interference caused by the phase difference of approximately π in the 45^o direction. At the same time, the scattered light of the core and shell constructively interfere in the 315^o direction.

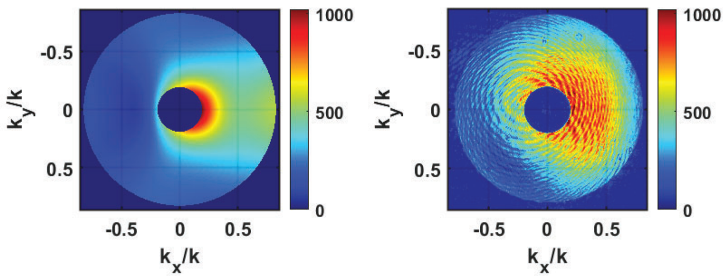
To validate the findings of the FEM simulations, the SiO_2 @ Au core-semishell CNP were fabricated and subsequently measured using a transmission Fourier microscope setup. The images of the measured CNP is shown



(a) Farfield magnitude (b) Phase difference

Fig. 1: a) Magnitude of the different electric fields scattered by a core-semishell particle calculated through the Lipmann-Schwinger integral equation (Equation 2); b) Phase difference between the fields scattered by the core and by the shell.

in Figure 2. From this preliminary measurement it can been seen that, like the FEM simulation, most light is scattered to the right side. Calculations show that 76% more light is scattered towards the right than the left.



(a) FEM simulation (b) Measurement

Fig. 2: Scattered field (Fourier space) (a) as calculated through FEM software, and (b) as measured using a transmission Fourier microscope setup . The scatter pattern is different from Figure 1, since the effect of the substrate has to be taken into account.

3. 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 scatter pattern found by the FEM software.

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