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ELECTRIC AND MAGNETIC DIPOLAR RESPONSE OF SMALL DIELECTRIC PARTICLES: SCATTERING ANISOTROPY AND OPTICAL FORCES

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Abstract. We predict that real small dielectric particles made of non-magnetic materials present non-conventional scattering properties similar to those previously reported for somewhat hypothetical magnetodielectric particles.

1. Introduction

In the presence of both electric and magnetic properties, the scattering characteristics of a small object present markedly differences with respect to pure electric or magnetic responses. Even in the simplest case of small or of dipolar scatterers, remarkable scattering effects of magnetodielectric particles were theoretically established by Kerker et al. [1] concerning suppression or minimization of either forward or backward scattering. Intriguing applications in scattering cancellation and cloaking together with the unusual properties of the optical forces on magnetodielectric particles [2] have renewed interest in the field. The striking characteristics of the scattering diagram of small (Rayleigh) magnetodielectric particles [1, 3] were obtained assuming arbitrary values of electric permittivity and magnetic permeability. Nevertheless, no concrete example of such particles that might present those interesting properties in the visible or infrared regions had been proposed.

Here, we show [4] that submicron dielectric spheres present dipolar magnetic and electric responses, characterized by their respective first-order Mie coefficient, in the near infrared, in such a way that either of them can be selected by choosing the illumination wavelength. Moreover, we will see that Si or Ge spheres constitute such a previously quested real example of dipolar particle with either electric and/or magnetic response, of consequences both for their emitted intensity [5, 6] and behavior under electromagnetic forces [2, 5, 7].

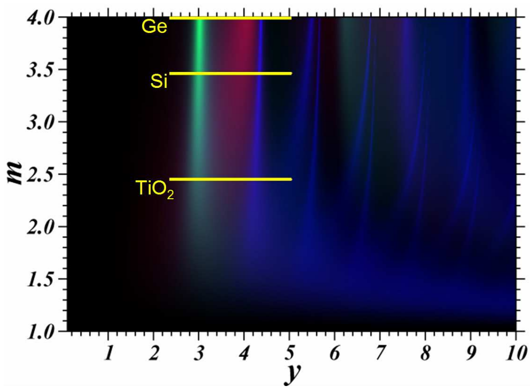

Figure 1. Scattering cross section map of a non-absorbing Mie sphere as a function of the refractive index m and the y parameter, $y = mka = m(2\pi a/\lambda)$. Green areas correspond to parameter ranges where the magnetic dipole contribution dominates the total scattering cross section, while red areas represent regions where the electric dipole contribution is dominating. The remaining blue-saturated areas are dominated by higher order multipoles. (Adapted from Ref. [4]).

2. Scattering Anisotropy

In Fig. 1 we show the scattering cross section map of a non-absorbing Mie sphere as a function of the refractive index m and the y parameter, $y = m(2\pi a/\lambda)$. For a pure electric or a pure magnetic dipolar particle (characterized by its electric, α_e, or magnetic, α_m, polarizabilities), in absence of interferences, the far field radiation pattern is symmetrically distributed between forward and backward scattering. However, when we consider the coherent contribution of both electric and magnetic dipoles, the radiation pattern is mainly distributed in the forward or backward region according to whether $\Re(\alpha_e \alpha_m^*)$ is positive or negative, respectively [2, 5]. Interestingly, at the so-called Kerker conditions, $\left|\epsilon^{-1}\alpha_e\right|^2 = |\mu\alpha_m|^2$, the scattered intensity should be independent of the incident polarization angle. The interference between electric and magnetic dipoles lead to a number of interesting effects:
i) The intensity in the backscattering direction can be exactly zero whenever $\epsilon^{-1}\alpha_e = \mu\alpha_m$. This anomaly corresponds to the so-called first Kerker condition [1], theoretically predicted for magnetodielectric particles having $\epsilon_p = \mu_p$.
ii) Although the intensity can not be exactly zero in the forward direction (causality imposes $\Im\{\alpha_e\}, \Im\{\alpha_m\} > 0$), *in absence of particle absorption, the forward intensity presents a minimum* at [5] $\Re\{\epsilon^{-1}\alpha_e\} = -\Re\{\mu\alpha_m\}$. For lossless magnetodielectric Rayleigh particles, this happens when [1, 3] $\epsilon_p = -(\mu_p - 4)/(2\mu_p + 1)$ and it is known as the second Kerker condition.

We show that *the two Kerker conditions also apply to purely dielectric spheres ($\mu_p = 1$) providing that their scattering properties may be described by the two first terms in the Mie expansion.*

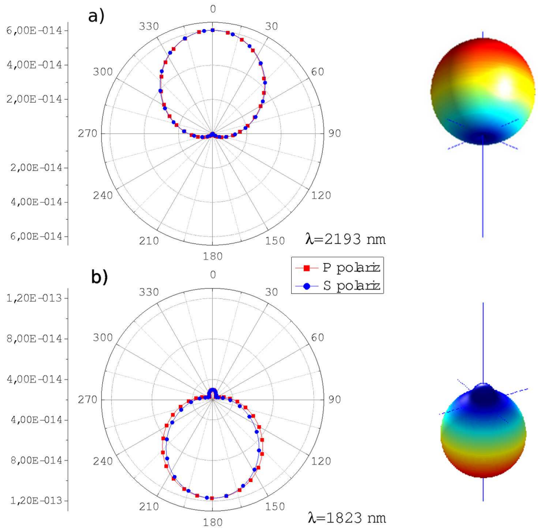

Figure 2. Scattering diagrams for the 240nm Ge nanoparticle of Fig. 1. (After Ref. [6]).

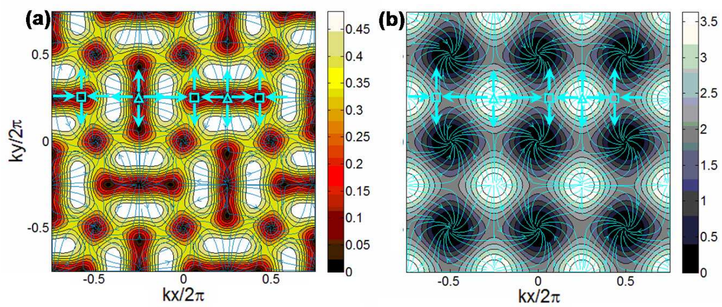

Figure 3. Nonconservative forces on a Si sphere of radius a = 230nm placed at the intersection region of two standing waves (After Ref. [7]) for a wavelength λ = 1725nm slightly above (red-shifted) the magnetic dipolar resonance. Arrows in (a) and (b) point along the total force lines. (a) Contour maps of the modulus of the normalized total force. (b) Contour maps of the normalized electric field intensity. (After Ref. [7]).

3. Optical Forces

We will discuss some of the consequences of the interference between magnetic and electric dipolar fields on optical forces [2, 5, 7]. We present a study of the total force on a small lossless dielectric particle, that presents both electric and magnetic response, in a optical vortex wave-field (see Fig. 3) . We show that the force is a simple combination of conservative and non-conservative steady forces that can rectify the flow of magnetodielectric particles. In a vortex lattice the electric-magnetic dipolar interaction can spin the particles either in or out of the whirls sites leading to trapping or diffusion. Specifically, we analyze force effects on submicron silicon spheres in the near infrared proving the results previously discussed for hypothetical magnetodielectric particles can be observed for these Si particles.

4. Conclusions

In summary, we have predicted that real small dielectric particles made of non-magnetic materials present non-conventional scattering properties similar to those previously reported for somewhat hypothetical magnetodielectric particles [1], resulting from an interplay between real and imaginary parts of both electric and magnetic polarizabilities. The exact scattering diagram, computed from the full Mie expansion, of submicron Si and Ge particles in the infrared was shown to be consistent with the expected result for dipolar electric and magnetic scattering. Then we showed that these unusual scattering effects do also affect the radiation pressure on these small particles;

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