DOI: 10.1478/C1V89S1P097

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 89, Suppl. No. 1, C1V89S1P097 (2011)

MAGNETIC RESPONSE FROM A COMPOSITE OF METAL-DIELECTRIC PARTICLES IN THE VISIBLE RANGE: T-MATRIX SIMULATION

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ABSTRACT. The optical response of a particle composed of a dielectric core surrounded by a densely packed shell of small metal spheres is simulated with the superposition T-matrix method for realistic material parameters. In order to compute the electric and magnetic particle polarizabilities a single expansion T-matrix is derived from a particle centered T-matrix. Finally the permeability of a medium comprising such particles is found to deviate considerable from unity resulting in a noticeable optical response.

1. Introduction

It is commonly assumed that the magnetic permeability is one in the visible range [1]. However, with the advent of artificial magnetism [2] this old postulate is not such indubitable anymore. Structures exhibiting magnetic response were already fabricated in planar technology [3], nevertheless a bulk medium with isotropic magnetic permeability is still to be demonstrated [4]. The most promising concepts in this regard, spherical metal dielectric composites, were treated either analytically disregarding all the terms except the dipoles [5] or numerically with finite difference methods [6]. As the search for structures and materials with isotropic magnetic response continues, a rigorous method is desirable for evaluation and optimization of particle materials and geometries. The T-matrix method [7], initially proposed to compute the scattering from conducting particles, was greatly extended over the following decades. In particular, light scattering from clusters of particles [8], and single origin representation of the cluster T-matrix [9] enable us to attribute a magnetic polarizability to a complex nano-structure. The next section is dedicated to the T-matrix treatment of these structures. Effective parameters of the media comprising such particles are discussed in Section **3**.

2. The individual magnetic resonator

Consider the structure depicted in Figure 1(left), it consists of a relatively large, $D =$ 80nm, dielectric core, surrounded by 51 small, $d = 24$nm, gold particles placed randomly on the surface. It was demonstrated on hand of approximate theories [5] that such a structure should exhibit a magnetic dipole response in the visible. To check whether the

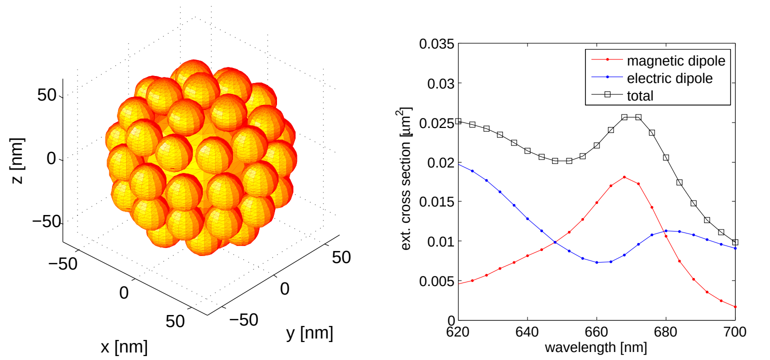

Figure 1. Schematic representation (left) of the composite particle with magnetic response: the larger dielectric core (d = 80nm) is surrounded by gold spheres ($d = 24$nm). Extinction cross section (right) of the composite: magnetic contribution (red line), electric contribution (blue line), total cross section (black line).

optical magnetic response can be obtained for realistic material parameters, the T-matrix of the cluster was computed. All results presented herein were obtained with Matlab$^{\mathrm{TM}}$ based programs developed in house. The dielectric particle consists of a 40nm silica core with a 10nm layer of magnetite and a further 10nm silica layer; the environment is water, $n = 1.33$. The magnetic layer is required to manipulate the particles by external fields and to induce the formation of chains. However, it does not introduce any magnetic response for the visible range. The black line in the Figure 1(right) shows the extinction cross section of the cluster in the range where the magnetic dipole resonance is expected. To estimate the character of the resonance a single origin cluster T-matrix is deduced [9]. The blue and the red curves in Figure 1(right) show the electric and magnetic dipole contributions to the cluster extinction. The increase in the cluster extinction can definitely be attributed to a magnetic dipole resonance, since in the same range the electric dipole response is quenched.

The electric and magnetic dipole polarizabilities α_{e} and α_{m} can be found from the expressions (6) in Ref. [10] and (5) in Ref. [11]. On adopting the notations from Ref. [12] concerning the sign of the Mie coefficients and the 4π factor, and presenting the Mie coefficients as the ratios of the corresponding expansion coefficients, the polarizabilities read as

$$\alpha_{\mathrm{e}} = -\mathrm{i}\frac{3}{2k^3}\frac{a^{\mathrm{s}}_{-11}}{a^{\mathrm{i}}_{-11}}, \qquad \alpha_{\mathrm{m}} = -\mathrm{i}\frac{3}{2k^3}\frac{b^{\mathrm{s}}_{-11}}{b^{\mathrm{i}}_{-11}}, \tag{1}$$

where k is the light wavenumber. a^{i}_{-11}, a^{s}_{-11} are the amplitudes of N_{-11} in the incident and the scattered field expansions of the cluster, and b^{i}_{-11}, b^{s}_{-11} are the respective amplitudes of their magnetic counterparts M_{-11} expressed in the cluster centered expansion.

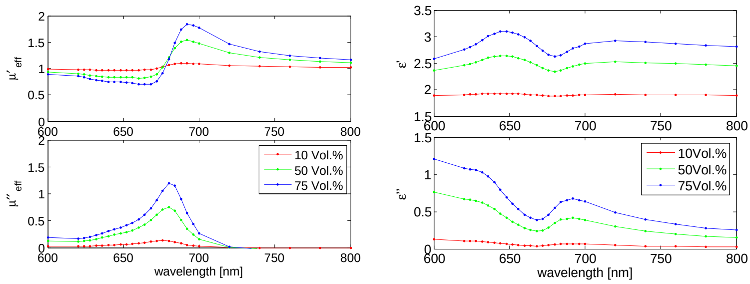

Figure 2. Effective permeability (left) and permittivity (right) estimates for different volume parts of magnetic resonantors.

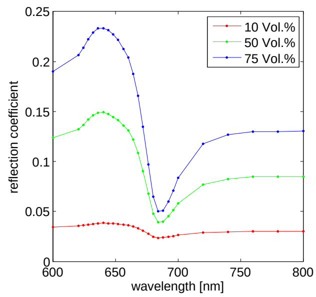

Figure 3. Reflection coefficient for the light falling normally from air on the magnetic medium. The red, green, and blue curves correspond to 10, 50 and 70 volume percents of magnetic particles in the medium.

3. Isotropic magnetic medium

The electric and magnetic dipole polarizabilities 1 can now be used to estimate the permeability and permittivity of a medium comprising optical magnetic resonators. An approximate expression is obtained from the Clausius-Mossotti theory [10, 12]

$$\varepsilon_{\mathrm{eff}} = \varepsilon \frac{1 + 2f\alpha_{\mathrm{e}}}{1 - f\alpha_{\mathrm{e}}}, \qquad \mu_{\mathrm{eff}} = \mu \frac{1 + 2f\alpha_{\mathrm{m}}}{1 - f\alpha_{\mathrm{m}}}, \tag{2}$$

where ε, μ are the permittivity and permeability of the environment, and $f = (4/3)\pi N$ is the coefficient dependent on the cluster concentration, N. Figure 2 shows the $\varepsilon_{\mathrm{eff}}$, μ_{eff} values computed for media with 10, 50 and 75 percent of the volume occupied by the magnetic clusters, with $N = 90$, 450 and 650 per cubic micrometer respectively. A rather dense suspension of magnetic particles is required to obtain significant shifts of the permeability. A characteristic feature of any resonant process in real systems is increased power loss, so the large imaginary part of μ_{eff} is not surprising, but may cause difficulties in transmission experiments. Nevertheless, the magnetic resonance can be observed in reflection as demonstrated in Figure 3, presenting the spectrum of the reflection coefficient for the normal incidence of light

$$R = \left| \frac{z - z_{\text{eff}}}{z + z_{\text{eff}}} \right|^2 ,$$

with $z = 1$ and $z_{\text{eff}} = \sqrt{\varepsilon_{\text{eff}}/\mu_{\text{eff}}}$. One expects a decrease in reflection where μ_{eff} is larger than 1 and more than 50% increase for $\mu_{\text{eff}} < 1$.

Acknowledgments

The authors gratefully acknowledge the support of BASF SE and the German Research Council (DFG), which, within the framework of its 'Excellence Initiative' supports the Cluster of Excellence 'Engineering of Advanced Materials' at the University of Erlangen-Nuremberg.

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Paper presented at the ELS XIII Conference (Taormina, Italy, 2011), held under the APP patronage; revised version published online 16 September 2011.