Size Evolution of the Fröhlich Resonance for Magnetic Nanoparticles

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Size effects on the dipolar plasmon resonance of small metallic particles were studied several years ago [1]. It is well known that for a spherical particle in the quasi-static limit (size$\rightarrow$0), the electric plasmon resonance, also called "Fröhlich resonance", appears at $\varepsilon=-2\varepsilon_m$, ε and ε_m being the electric permittivity of the particle and the surrounding medium, respectively. However, for finite size particles but still smaller than the incident wavelength, the plasmon mode is slightly shifted to the red part of the spectrum and follows the relation

$$\varepsilon = -(2 + \frac{12}{5}x^2)\varepsilon_m \qquad (1)$$

where $x = kR = \left(\frac{2\pi}{\lambda}R\right)$ is the size parameter, R is the radius of the particle, k the wavenumber and λ the incident wavelength.

This theoretical result was obtained for particles that only have electric properties ($\mu=1$). However, the new engineered materials, known as *metamaterials* [2], are providing us with structures (from micro to nano scales) [3, 4] that respond to both the electric and the magnetic part of the incident field. Recent studies have extended this kind of materials from microwaves to the visible part of the spectrum, with the appearance of new phenomena like the negative refraction [5]. Also, metamaterials force us to generalize the well-known scattering theories by considering diffusers with electric and magnetic properties [6]. In particular, we have devoted this work to the analysis of the dipolar plasmon resonance, "the Fröhlich resonance", for scatterers with unconventional optical properties.

Although metamaterials are internally structured or present complex geometries [7], when λ is long enough compared with their inner structures, we can model them as spherical particles with given size and effective optical properties [8]. In this sense, we have considered the diffuser system as a single spherical nanoparticle with ε and μ different from 1. In Fig. 1, we show the evolution of the electric permittivity for which the electric plasmon resonance is excited ($\varepsilon_{\text{resonant}}$) as a function of both the particle size and the magnetic permeability. It can be seen that if the particle size approaches zero, the resonant permittivity is located at ε=-2 (supposed $\varepsilon_m=1$). If $\mu=1$ (Fig. 1a), as R changes the section of the curve can be described with Eq. (1). However, for $\mu\neq1$ the behavior becomes more complex. Also, if we consider negative values for the magnetic permeability (Fig. 1b), the size evolution of the resonance is even more complex than the positive case. In order to explain these new features, we have made a detailed analysis of the first Mie coefficient, a_1 (which produces the plasmon resonance), obtaining the equivalent relation to Eq.(1) but including the magnetic contribution. Finally, by means of the ε–μ symmetry that present the two first Mie coefficients [1], the results for the electric plasmon resonance, due to maximum values of a_1, can be extended to the magnetic plasmon mode (maximum values of b_1).

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Figures

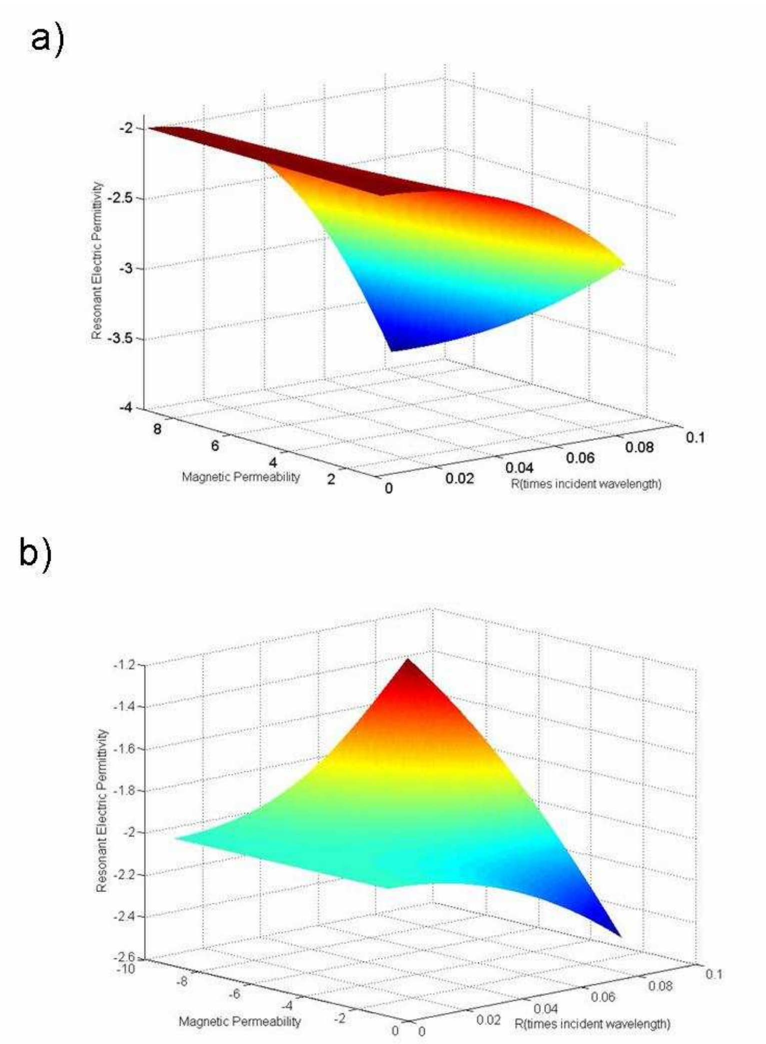

Fig. 1. 3D plot of the evolution of the resonant electric permittivity ($\varepsilon_{resonant}$) for a spherical small particle as a function of the particle size (R) and the magnetic permeability (μ). μ has been considered either positive (a) or negative (b).

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