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Enhanced extinction of electromagnetic radiation by metal-coated fibers

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Abstract

The scattering properties of metal-coated fibers are studied. It is shown that an optimal thickness of the metal layer exists, for which the extinction efficiency can significantly exceed the extinction efficiency of uncoated homogeneous metal fibers of identical size. At the same time the scattering efficiency of coated fibers remains lower than that of the homogeneous ones.

Keywords: Light scattering; Coated fibers; Enhancement factor; Nonspherical particles

1. Introduction

Numerous works have been addressed to the study of the resonance effects of spherical and nonspherical small particles, including coated and multi-layered structures. One has to distinguish here between several different phenomena. First, there are the smooth maxima of the extinction and scattering efficiencies as a function of size parameter x in the region $x \approx 1$. These exist for homogeneous particles and for multi-layered structures as well. There are also the narrow resonant peaks superimposed upon these maxima, if the frequency is close to a natural one [1], and often called a "morphology dependent resonance" [2]. Additional resonant peaks appear in the case of multi-layered particles, which have a direct analogy with the plain-layered structures. The resonance phenomenon takes place also for small (compared to wavelength) spherical particles and high (optical or higher) frequencies. It relates to the so-called surface (Frölich) modes and was described in the literature for homogeneous [2], coated [3], and multi-layered particles [4].

In the present work we investigate metal-coated fibers with a diameter much smaller than the wavelength. Furthermore, the optical thickness of the metal layer is also much less than the wavelength. However, the frequencies we deal with are much lower than the natural (or Frölich) ones, thus the resonance discussed above is not expected here. Since one cannot expect any essential effect for spherical particles, we consider only cylindrical ones where the electric field of the incident wave has the component parallel to the cylinder axis. For such fibers one can obtain an interesting effect. It reveals itself in the existence of an optimal coating

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thickness providing the maximal extinction efficiency, which turns out to be significantly larger than that for the homogeneous metal particle with the same outer size. At the same time, the scattering efficiency remains smaller than that of the homogeneous fiber.

2. Basic considerations

Here we demonstrate the existence of an optimal thickness for certain combinations of dielectric and metal materials (we do not call this effect a resonance in order to avoid the confusion with the common use of this term).

Consider the cross section of a metal-coated cylinder having the core radius r and the outer radius R. The coating thickness $d = R - r$. The extinction efficiency can be represented as a sum of scattering and absorption contributions, $Q_{\mathrm{ext}} = Q_{\mathrm{sc}} + Q_{\mathrm{abs}}$. For a given core and coating materials, and a fixed core radius, both Q_{sc} and Q_{abs} are functions of d. The scattering efficiency rises with increasing coating thickness, approaching a value calculated for a homogeneous metal particle of the same size. On the other hand, Q_{abs} depends on d in a more complicated way. For a very thin coating it must rise with an increase of coating thickness. However, increasing d further leads to a significant decrease of the field penetrating the particle, and thus one can expect a reduction of the absorption efficiency.

This suggests that there may exist an optimal thickness, d_0,

$$\frac{\partial}{\partial d}(Q_{\mathrm{abs}} + Q_{\mathrm{sc}})_{|d=d_0} = 0. \tag{1}$$

Since the analytical treatment of the proper expressions is cumbersome, we illustrate the idea in a rather rough approximation, where the arguments of the Bessel functions are presumed small enough that only the first terms (the first two for J_0) in the series are kept. Additionally, we assume that the metal coating provides that only the zero order term in the Mie solution contributes significantly. Consider a coated infinitely long fiber, illuminated by a normally incident wave with electric field $\mathbf{E}_{\mathrm{in}}$ parallel to the fiber axis. Within this approximation Q_{ext} is proportional to $Re\{b_0\}$.

Let m_1 be the refraction index of the core, and m_2 the refraction index of the metal layer, $|m_1| \ll |m_2|$. For normal incidence we have [5]

$$b_0 = \frac{J_0(x_2)}{H_0^{(1)}(x_2)} \frac{m_2 H_0^b - D_0^{(1)}(x_2)}{m_2 H_0^b - D_0^{(3)}(x_2)}. \tag{2}$$

Here

$$H_0^b = \frac{P_0(m_2 x_2) D_0^{(1)}(m_2 x_2) - B_0 D_0^{(2)}(m_2 x_2)}{P_0(m_2 x_2) - B_0}, \tag{3}$$

$$B_0 = P_0(m_2 x_1) \frac{m_2 D_0^{(1)}(m_1 x_1) - m_1 D_0^{(1)}(m_2 x_1)}{m_2 D_0^{(1)}(m_1 x_1) - m_1 D_0^{(2)}(m_2 x_1)}, \tag{4}$$

where according to commonly used notations:

$$D_n^{(1)}(z) = \frac{J_n'(z)}{J_n(z)}, \quad D_n^{(2)}(z) = \frac{Y_n'(z)}{Y_n(z)}, \quad D_n^{(3)}(z) = \frac{H_n^{(1)'}(z)}{H_n^{(1)}(z)}$$

and

$$P_n(z) = \frac{J_n(z)}{Y_n(z)}, \quad x_1 = kr, \quad x_2 = kR.$$

In our case $H_0^{(1)}(z) \approx \mathrm{i} Y_0(z)$, and further;

$$B_0 \approx P_1(m_2 kr), \tag{5}$$