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Extinction properties of metallic nanowires: Quantum diffraction and retardation effects

Afshin Moradi [a,b,*]

[a] Department of Engineering Physics, Kermanshah University of Technology, Kermanshah, Iran
[b] Department of Nano Sciences, Institute for Studies in Theoretical Physics and Mathematics (IPM), Tehran, Iran

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ABSTRACT

The standard Mie theory for the extinction of electromagnetic radiation by a metal cylinder that is irradiated by a normally incident plane wave is extended to the case of a metallic nanowire, where two quantum longitudinal waves are excited. The modification of the Mie theory due to quantum diffraction effects is included by employing the quantum hydrodynamic approximation and applying the appropriate quantum additional boundary conditions. The extinction properties of the system and their differences with previous treatments based on the standard local and nonlocal models are shown. Also, as an example the validity of the nonretarded approximation in the quantum nonlocal optical response of a sodium nanowire is discussed.

1. Introduction

The theory of light scattering by infinite metallic nanowires and nanotubes has been extended by several authors [1]. Considering a thin nanowire, the standard electromagnetic scattering formalism for a circular cylinder was extended in Ref. [2] to include longitudinal plasmon resonances. Boustimi et al. [3] determined the nonlocal linear optical response of a nanowire in the framework of the self-consistent method and a jellium model. The theoretical study of the effect of wall thickness on the light scattering from homogeneous gold single-walled nanotubes has been investigated by Zhu [4]. Wu et al. [5,6] calculated the extinction spectra of two-layered homogeneous gold nanowires, by using the vector wave function method. Raza et al. [7,8] studied the optical properties of spatially dispersive nanowires and nanotubes and they found that unusual resonances due to nonlocal response do exist in plasmonic nanowires, but only above the plasma frequency, not in the visible. Hewageegana [9] used a theoretical model for the static polarizability of a nanowire that allows the inclusion of nonlocal effects, according to the method of Refs. [10,11]. Also, the electromagnetic wave scattering from the metallic single-walled carbon nanotubes are studied in [12,13]. In this way, recently we derived the extinction properties of the random metal–dielectric nanocomposite cylinders, and investigated the dependence of the extinction spectrum on the nanoparticles' shape and concentration as well as on the cylinder radius and the incidence angle for both TE and TM polarization [14].

Furthermore, Li and Yin [15] investigated the optical response of a metallic nanowire using both the Drude and standard hydrodynamic (SHD) models. By comparing the results of two models, they found that the Fano-like resonances of subsidiary peaks originated from the nonlocality. However, as mentioned in [16] the nonretarded SHD theory gives rise to spurious oscillations in the plasmon spectra of metallic nanostructures with sharp tips or narrow gaps [17,18]. As a result the SHD theory may not be applicable for investigating the nonlocal effects of electron excitations in nanometer-sized structures, because it ignores the quantum nature of the excited electrons in the metal. Inspired by the above result, we used the quantum hydrodynamic (QHD) model [19–26] and studied the quantum nonlocal (QNL) polarizability of a metallic nanowire, in the quasistatic approximation [27]. Also, we discussed the QNL effects on the surface and bulk plasmon modes of a cylindrical metallic nanowire in the nonretarded approximation, thus neglecting retardation effects [28]. In the present work, we wish to develop the previous results [2,27,28] and discuss the QNL effects on the extinction properties of metallic nanowires in the presence of the retardation effects. In this way, by employing the linearized QHD theory and applying the appropriate additional quantum boundary conditions, we extend the classical Mie theory for the extinction of electromagnetic radiation by a metallic nanowire, where two quantum longitudinal waves are excited.

* Correspondence to: Department of Engineering Physics, Kermanshah University of Technology, Kermanshah, Iran.
E-mail address: a.moradi@kut.ac.ir.

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This paper has the following structure. In Section 2, we extend the QNL electrostatic approximation to develop a retarded theory by including retardation effects into the calculations. In Section 3, we use the retarded model to derive extinction spectra of a sodium nanowire and results are compared with previous works. We then conclude with a summary of our results in Section 4.

2. Theory

Let us consider an unmagnetized cylindrical nanowire of radius a and infinite length that aligned along the z-axis and surrounded by a homogeneous dielectric environment with permittivity ε_M. We use cylindrical coordinate (ρ, ϕ, z) for an arbitrary point in space. In the present system, the metal supports both the usual transverse and quantum longitudinal waves and above the plasma frequency both types of waves can propagate. Here it is assumed that the QNL responses of the system are dominated by the quantum nonlocality induced by free electron gas, while the bound electrons only contribute to local responses. Thus in the hydrodynamic model, the dielectric properties of nanowires are characterized by both the usual Drude transverse dielectric function, as

$$\epsilon_T = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \tag{1}$$

and the QHD longitudinal dielectric function [20]

$$\epsilon_L = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma) - \alpha^2 k^2 - \beta^2 k^4}, \tag{2}$$

where ω is the frequency, k is the QNL longitudinal wave vector, ω_p is the classical plasma frequency in homogeneous electron quantum plasma. Also, ϵ_∞ in general is frequency-dependent and takes into account those polarization effects that are not due to the free electrons, such as interband transitions [27,29], $\alpha = \sqrt{3/5}v_F$, and $\beta = \hbar/2m_e$. We note that the second term in denominator of Eq. (2) is regarded as the quantum statistical effect caused by the internal interactions in the electrons species and the third term regarded as quantum diffraction effect comes from the quantum pressure.

Now, we assume that the system be exposed by a normally incident beam in which the electric field of it is perpendicular to the cylinder axis. This is the polarization for which the excitation of longitudinal quantum plasma modes occurs. When the incident electric field is parallel to the cylinder axis, no surface and bulk plasmon resonance peaks are found in the far-field spectra (not shown here) because the polarization direction along the axis of quantum wire cannot induce the collective motions of the conduction electrons.

The vector cylindrical harmonics functions can be defined according to Ref. [30] as follows:

$$\mathbf{M}_m = \nabla \times [\mathbf{e}_z Z_m(k\rho)\exp(im\phi)], \tag{3}$$

$$\mathbf{N}_m = (1/k)\nabla \times \mathbf{M}_m, \tag{4}$$

$$\mathbf{L}_m = \nabla[Z_m(k\rho)\exp(im\phi)]. \tag{5}$$

In component form these vector harmonics are

$$\mathbf{M}_m = k\left(\mathbf{e}_\rho \frac{imZ_m(k\rho)}{k\rho} - \mathbf{e}_\phi Z'_m(k\rho)\right)\exp(im\phi),$$

$$\mathbf{N}_m = \mathbf{e}_z k Z_m(k\rho)\exp(im\phi),$$

$$\mathbf{L}_m = \left(\mathbf{e}_\rho k Z'_m(k\rho) + \mathbf{e}_\phi \frac{imZ_m(k\rho)}{\rho}\right)\exp(im\phi).$$

Here k is given by $k_T = \sqrt{\varepsilon_T}\omega/c$ for the transverse modes and

$$k_L^\pm = \left\{-\frac{\alpha^2}{2\beta^2} \pm \frac{\alpha^2}{2\beta^2}\left[1 + \frac{4\beta^2}{\alpha^4}\left[\omega(\omega + i\gamma) - \frac{\omega_p^2}{\epsilon_\infty}\right]\right]^{1/2}\right\}^{1/2},$$

for the longitudinal modes inside the nonmagnetic quantum cylinder and by $k_M = \sqrt{\varepsilon_M}\omega/c$ outside it, where c is the light speed in vacuum. Also, $\mathbf{e}_\rho$, $\mathbf{e}_\phi$, and $\mathbf{e}_z$ are unit vectors in ρ, ϕ, and z directions, respectively, and $Z_m(k\rho)$ represents a cylindrical Bessel or Hankel function, and is chosen as follows. Inside the cylinder $J_m(k_T\rho)$ is used for the transverse modes and $J_m(k_L^+\rho)$ and $J_m(k_L^-\rho)$ are used for the quantum longitudinal modes. Outside the cylinder $J_m(k_M\rho)$ and $H_m(k_M\rho)$ are used for the incident and scattered waves, respectively. We note that the Hankel function is chosen to indicate that the scattered field is a wave traveling in the outward radial direction. The expansion of the incident electromagnetic field is

$$\mathbf{E}_i = -i\sum_{m=-\infty}^{+\infty} E_m \mathbf{M}_m(k_M\rho), \tag{6}$$

$$\mathbf{H}_i = -\frac{k_M}{\omega\mu_0}\sum_{m=-\infty}^{+\infty} E_m \mathbf{N}_m(k_M\rho), \tag{7}$$

where $E_m = E_0(-i)^m/k_M$. The expansion of the transmitted and scattered electromagnetic fields can be represented as

$$\mathbf{E}_t = \sum_{m=-\infty}^{+\infty} g_m E_m \mathbf{M}_m(k_T\rho), \tag{8}$$

$$\mathbf{H}_t = -\frac{ik_T}{\omega\mu_0}\sum_{m=-\infty}^{+\infty} g_m E_m \mathbf{N}_m(k_T\rho), \tag{9}$$

$$\mathbf{E}_s = \sum_{m=-\infty}^{+\infty} ia_m E_m \mathbf{M}_m(k_M\rho), \tag{10}$$

$$\mathbf{H}_s = -\frac{ik_M}{\omega\mu_0}\sum_{m=-\infty}^{+\infty} ia_m E_m \mathbf{N}_m(k_M\rho). \tag{11}$$

Furthermore, in the nanowire, at the same frequency ω, there are two quantum longitudinal waves (bulk plasmons) that can be described by the following electric fields

$$\mathbf{E}_L^+ = \sum_{m=-\infty}^{+\infty} h_m^+ E_m \mathbf{L}_m(k_L^+\rho), \tag{12}$$

$$\mathbf{E}_L^- = \sum_{m=-\infty}^{+\infty} h_m^- E_m \mathbf{L}_m(k_L^-\rho). \tag{13}$$

The unknown expansion coefficients a_m, g_m, h_m^+, and h_m^- can be determined by the appropriate boundary conditions at the surface of the cylinder. The usual two classical boundary conditions at the plasma–dielectric interface require the continuity of the tangential components of the electric and magnetic fields across the interface. We note that in the nanowire both the transverse and longitudinal (usually neglected) waves give a contribution to the value of electric field, we have

$$\left(E_{i\phi} + E_{s\phi}\right)|_{\rho=a} = \left(E_{t\phi} + E_{L\phi}^+ + E_{L\phi}^-\right)|_{\rho=a}, \tag{14}$$

$$\left(H_{iz} + H_{sz}\right)|_{\rho=a} = H_{tz}|_{\rho=a}. \tag{15}$$

Since we have allowed for the excitation of the two quantum longitudinal modes inside the cylinder, the two above boundary conditions are not sufficient to determine the scattering amplitudes