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Relativistic energy loss and induced photon emission in the interaction of a left-handed sphere with an external electron beam

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Abstract

Relativistic energy loss and photon emission in the interaction of a coated sphere containing a left-handed material with an external electron beam are studied based on the classical electrodynamics. Both of electric modes and magnetic modes are not only found in the spectra of energy loss and photon emission for different combinations of electron velocity and sphere radius, the new excitation modes can be also observed. Our results show that different excitation modes for the left-hand materials and the structure information of coated sphere can be explored by scanning transmission electron microscopy (STEM).

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1. Introduction

Scanning transmission electron microscopy (STEM) has proved to be a powerful technique for determining different microstructures of nanometer scale [1]. The interaction between the electron and the microstructures gives rise to the emission and excitation of the radiation. Thus, the electron energy loss spectroscopy (EELS) in the STEM is also a useful tool to investigate both surface and bulk excitations of the samples [2–19]. In the last decades a remarkable progress has been made on this subject [2–19]. Various geometrical objects have been investigated and many interesting results have been obtained [2–19]. However, the above investigations all focus on the dielectric or metal systems.

Recently, left-handed materials (LHMs) have attracted a great deal of attention from both theoretical and experimental sides [20–23]. These materials, which are characterized by simultaneous negative permittivity and permeability, possess a number of unusual electromagnetic effects [20–23]. One of them is that negative refraction can occur at the interface between the LHMs and a positive (conventional) medium. In fact, the phenomena of negative refraction of waves at interfaces had been analyzed theoretically by Mandel'shtam in the early 1940s [23,24], but only recently they were demonstrated experimentally [21]. Very recently, surface polarized modes around left-handed slab, cylinder and sphere have also been studied theoretically [25,26]. Some researches [27–31] have shown that the total scattering cross of the objects can be reduced by using metamaterials to cover them, which makes these objects nearly "invisible" or "transparent" to an outside observer. It is a natural question to ask whether or not these unusual properties and surface modes can be explored by the STEM? Whether or not they can be excited by the moving electron beam?

Considering the above problems, in this Letter we will investigate the relativistic energy loss and photon emission in the interaction of a coated sphere containing the left-handed materials with an external electron beam. Our studies are based on the theory of classical electrodynamics. We first extend the analytical method of the energy loss, which has been developed in Ref. [15] for the single dielectric sphere, to the coated sphere containing the left-handed material. Subsequently, we calculate the variation of the energy-loss spectra and the photon emission

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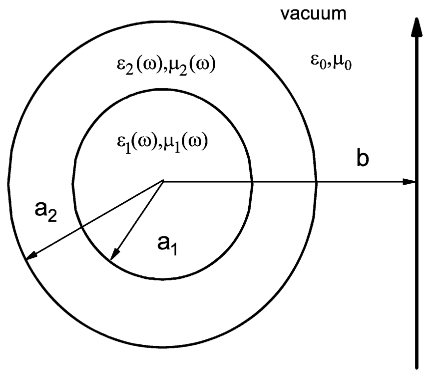

Fig. 1. Schematic picture of the geometry depicting a moving electron in vacuum with velocity v in the interaction of a spherical particle composed of two concentric layers of different isotropic materials.

with the different combinations of electron velocity, impact parameter, the size and structure of the coated sphere by using such a method.

2. Theory

We consider a fast electron moving along a straight-line trajectory with constant velocity v and passing near a coated sphere containing the left-handed material located in vacuum, as shown in Fig. 1. The left-handed material is characterized by the dispersive permittivity ($\varepsilon(\omega)$) and permeability ($\mu(\omega)$), which are both negative in a certain frequency region, and have the following forms [21,24,25]:

$$\varepsilon(\omega)=1-\frac{\omega_p^2}{\omega(\omega+i\gamma)} \tag{1}$$

and

$$\mu(\omega)=1-\frac{F\omega^2}{\omega^2-\omega_0^2+i\omega\Gamma}, \tag{2}$$

where ω_p is plasma frequency, γ and Γ are the respective electric and magnetic loss terms. ω_0 is the magnetic resonance frequency. The radii of the inner core and the shell are a_1 and a_2, respectively. Without loss of generality, the electron trajectory will be chosen parallel to the z axis with impact parameter b with respect to the origin of coordinates (the center of the coated sphere).

When an electron moves along a straight-line trajectory and passes near the coated sphere, it may engender collective excitations that act back upon the electron, which leads to the energy loss of the moving electron. The energy loss can be related to the force exerted by the induced electric field E^{ind} acting on it as [15]

$$\Delta E^{\text{loss}}=\int dt\,\vec{v}\cdot\vec{E}^{\text{ind}}(\vec{r}_t,t)=\int_0^\infty \omega\,d\omega\,\Gamma^{\text{loss}}(\omega), \tag{3}$$

where

$$\Gamma^{\text{loss}}(\omega)=\frac{1}{\pi\omega}\int dt\,\operatorname{Re}\bigl\{e^{-i\omega t}\vec{v}\cdot\vec{E}^{\text{ind}}(\vec{r}_t,\omega)\bigr\} \tag{4}$$

is the so-called loss probability, which can be divided into the contributions of magnetic and electric modes,

$$\Gamma^{\text{loss}}=\Gamma^{M,\text{loss}}+\Gamma^{E,\text{loss}}. \tag{5}$$

Here

$$\Gamma^{M,\text{loss}}(\omega)=\sum_{l=1}^{\infty}\sum_{m=-l}^{l}\frac{mv}{\pi\omega^2}K_m\left(\frac{\omega b}{v\gamma}\right)\times\operatorname{Re}\bigl\{\bigl(A_{lm}^{+}\bigr)^{*}e^{im\varphi_0+i\omega z_0/v_i-l}\psi_{lm}^{M,\text{ind}}\bigr\} \tag{6}$$

and

$$\Gamma^{E,\text{loss}}(\omega)=\sum_{l=1}^{\infty}\sum_{m=-l}^{l}\frac{c}{2\pi\omega^2\gamma}K_m\left(\frac{\omega b}{v\gamma}\right)\times\operatorname{Re}\bigl\{B_{lm}^{*}e^{im\varphi_0+i\omega z_0/v_i-l}\psi_{lm}^{E,\text{ind}}\bigr\}, \tag{7}$$

where $\psi_{lm}^{M,\text{ind}}$ and $\psi_{lm}^{E,\text{ind}}$ represent the induced scattered fields, which can be expressed as

$$\psi_{lm}^{M,\text{ind}}=t_l^M\psi_{lm}^{M,\text{ext}} \tag{8}$$

and

$$\psi_{lm}^{E,\text{ind}}=t_l^E\psi_{lm}^{E,\text{ext}}. \tag{9}$$

Here t_l^M and t_l^E are the scattering-matrix elements of the coated sphere, which can be obtained from Mie's scattering theory in the following form [25]:

$$t_l^M=-\frac{A_l^1}{A_l^2} \tag{10}$$

and

$$t_l^E=-\frac{B_l^1}{B_l^2}, \tag{11}$$

where

$$\begin{aligned}A_l^1={}&\bigl\{\bigl[k_0a_2j_l(k_0a_2)\bigr]'j_l(k_2a_2)/\mu_0\\&-j_l(k_0a_2)\bigl[k_2a_2j_l(k_2a_2)\bigr]'/\mu_2\bigr\}\\&\times\bigl\{\bigl[k_2a_1n_l(k_2a_1)\bigr]'j_l(k_1a_1)/\mu_2\\&-n_l(k_2a_1)\bigl[k_1a_1j_l(k_1a_1)\bigr]'/\mu_1\bigr\}\\&+\bigl\{\bigl[k_2a_2n_l(k_2a_2)\bigr]'j_l(k_0a_2)/\mu_2\\&-n_l(k_2a_2)\bigl[k_0a_2j_l(k_0a_2)\bigr]'/\mu_0\bigr\}\\&\times\bigl\{\bigl[k_2a_1j_l(k_2a_1)\bigr]'j_l(k_1a_1)/\mu_2\\&-j_l(k_2a_1)\bigl[k_1a_1j_l(k_1a_1)\bigr]'/\mu_1\bigr\},\end{aligned} \tag{12}$$

$$\begin{aligned}B_l^1={}&\bigl\{\varepsilon_2\bigl[k_0a_2j_l(k_0a_2)\bigr]'j_l(k_2a_2)\\&-\varepsilon_0j_l(k_0a_2)\bigl[k_2a_2j_l(k_2a_2)\bigr]'\bigr\}\\&\times\bigl\{\varepsilon_1\bigl[k_2a_1n_l(k_2a_1)\bigr]'j_l(k_1a_1)\\&-\varepsilon_2n_l(k_2a_1)\bigl[k_1a_1j_l(k_1a_1)\bigr]'\bigr\}\\&+\bigl\{\varepsilon_0\bigl[k_2a_2n_l(k_2a_2)\bigr]'j_l(k_0a_2)\\&-\varepsilon_2n_l(k_2a_2)\bigl[k_0a_2j_l(k_0a_2)\bigr]'\bigr\}\end{aligned}$$