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Surface plasmon resonant scattering in metal-coated dielectric nanocylinders

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The scattering of TE polarized plane wave by metal-coated dielectric nanocylinders is investigated with a particular emphasis on the enhancement of the near fields. If the wavelength of illumination is properly chosen, two unique near field distributions can be excited through the surface plasmon resonances. The enhanced near fields are localized along the inner or outer interface of the coating metal, being dependent on the wavelengths. It is shown that the scattering cross-section of the nanocylinders is also enhanced when the illuminating field resonates to the surface plasmons of the structures.

1. Introduction

With the rapid development of nanoscience and nanotechnology, the interaction of light with nanoscale objects remains as an important topic in recent years [1,2] because of their wide range of applications to the optical sensors, imaging, and integrated devices. The literature on the interaction of light with nanoscale objects in general is of course much broader. The study on the interaction can be organized in many different ways, being dependent on the dimensionality of the objects and the exciting source. We shall focus here our consideration on the cylindrical structures, which are usually called as nanocylinders or nanowires.

The visible-light absorption by silicon nanocylinders was reported in [3]. This study explained the optical ignition phenomena in nanoscale objects. The anomalous light scattering and the peculiarities of energy flux around a thin nanowire under surface plasmon resonances were discussed in [4]. The surface plasmons characterize the unique response in collective motions of electrons on a metal–dielectric interface [5,6], which is allowed when the permittivity of the metal is negative for the wavelength of excitation. The full wave analysis of the dispersion relation and field distribution of surface plasmon plaritons on metal cylinders with a dielectric core were presented [7] by taking into account the retardation. An experimental technique to determine the dispersion relation of the surface plasmon polaritons on Ag and Au nanowires was reported in [8]. The basic concept underlying the existence of surface plasmons in metallic structures was reviewed in [9].

The enhanced surface plasmon resonance in noble metallic nanocylinder systems at optical frequencies is expected to be a promising issue for realizing excellent scatterers and absorbers of visible light. The plasmon resonances of interacting silver nanocylinders were analyzed [10] for both non-touching and intersecting configurations and the enhanced scattering through the plasmon resonant coupling was discussed using the finite element analysis. The surface plasmon resonances and near-field properties of nanocylinders with a cap-shaped or shell-shaped metal coating were numerically investigated in [11] using the finite-element method. The anomalous light scattering by a nanocylinder near plasmon resonance wavelengths was demonstrated in [12]. The enhanced backscattering by metallic nanocylinder arrays near surface plasmon resonances was discussed in [13]. Recently, much attention has been paid to the light scattering from nanocylinders with a metal–dielectric layered structure. The superscattering [14,15] and cloaking [15] of light in core–shell nanocylinders were investigated in detail.

In this paper, the scattering of TE polarized plane wave by metal-coated dielectric nanocylinders is investigated with a particular emphasis on the enhancement of the near fields. There exist two kinds of surface plasmons in the metal-coated nanocylinders. One is the surface plasmons localized along the inner interface of the metal layer and the other is localized along the outer interface. If the wavelength of illumination is properly chosen, the illuminating

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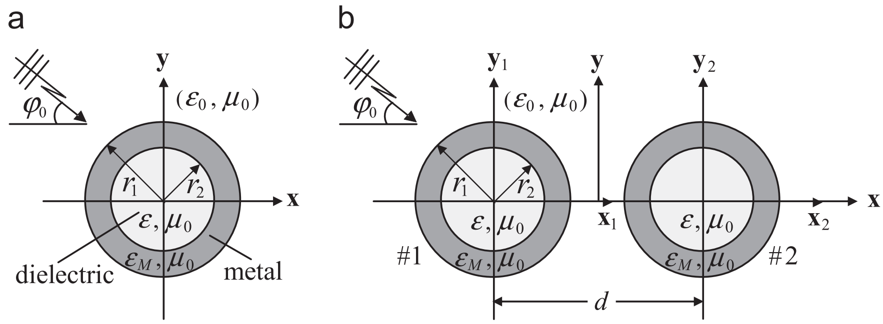

Fig. 1. Cross-section of metal-coated circular nanocylinders illuminated by a TE plane wave which is incident normally to the cylinder axis; (a) single cylinder system and (b) two cylinders system.

field resonates to each of surface plasmons and the unique near field distributions are excited along the cylinders. Numerical results demonstrate that the enhanced near fields are localized around two interfaces of the coating metal layer and closely related to the surface plasmon resonances. It is also shown that the spectral responses of the scattering cross-section of the metal-coated nanocylinders take a peak value at the wavelengths of surface plasmon resonances.

2. Formulation of the problem

The cross-section of coaxial cylindrical structures to be considered here is shown in Fig. 1. The coaxial cylinder with outer radius $r_1$consists of a circular dielectric core with radius r_2 and a metal coating layer of thickness r_1-r_2. The coaxial cylinder is infinitely long in the z direction and placed in free space. The material constants of the outer free space, coating metal, and dielectric core are denoted by(ε_0,μ_0),(ε_M,μ_0), and (ε,μ_0), respectively. Fig. 1 shows the configurations of (a) a single coaxial cylinder and (b) two identical coaxial cylinders separated by a distance $d$along the x axis. The cylindrical structures are illuminated by a plane wave of unit amplitude which propagates normally to the cylinder axis. The angle of incidence of the plane wave is φ_0 with respect to the x axis. The scattering problem is two-dimensional and hence the electric and magnetic fields are decomposed into TE-wave . Since we are interested in the scattering problem related to the plasmon resonances, we focus our investigation on the scattering of TE wave with $(H_z, E_x,\ E_y)$component.

Let us consider first the scattering by a single coaxial cylinder shown in Fig. 1(a). The reflection and transmission of the standing and outgoing cylindrical waves on the two cylindrical interfaces ($\rho=r_1$ and $\rho=r_2$) are solved separately in the referenced coordinate system (ρ,φ) in x–o–y. This leads to the reflection and transmission matrices for cylindrical harmonic waves at each of the interfaces, which are concatenated to obtain the generalized reflection and transmission matrices [16,17] over two cylindrical interfaces. If we denote by the column vectors ($\mathbf{\Phi}_0$, $\mathbf{\Phi}_M$, $\mathbf{\Phi}_D$) and ($\mathbf{\Psi}_0$, $\mathbf{\Psi}_M$) the set of basis functions for the standing cylindrical waves and outgoing cylindrical waves in respective regions, the solutions to the H_z field in three regions of Fig. 1(a) are obtained as follows:

$$H_z=\mathbf{\Phi}_0^T\cdot p+\mathbf{\Psi}_0^T\cdot\mathbf{T}\cdot\boldsymbol{p} \quad \text{for} \quad r_1<\rho \tag{1}$$

$$H_z=\mathbf{\Phi}_M^T\cdot\mathbf{B}\cdot p+\mathbf{\Psi}_M^T\cdot\mathbf{C}\cdot\boldsymbol{p} \quad \text{for} \quad r_2<\rho<r_1 \tag{2}$$

$$H_z=\mathbf{\Phi}^T\cdot\mathbf{D}\cdot\boldsymbol{p} \quad \text{for} \quad 0<\rho<r_2 \tag{3}$$

with

$$\left.\begin{array}{ll}\mathbf{\Phi}_0=[J_m(k_0\rho)e^{im\varphi}], & \mathbf{\Psi}_0=[H_m^{(1)}(k_0\rho)e^{im\varphi}]\\ \mathbf{\Phi}_M=[J_m(k_M\rho)e^{im\varphi}], & \mathbf{\Psi}_M=[H_m^{(1)}(k_M\rho)e^{im\varphi}]\\ \mathbf{\Phi}=[J_m(k\rho)e^{im\varphi}] & \end{array}\right\} \tag{4}$$

$$\boldsymbol{p}=[p_m], \quad p_m=i^m e^{im\varphi_0} \quad (0^\circ\le\varphi_0\le180^\circ) \tag{5}$$

$$k_0=\omega\sqrt{\varepsilon_0\mu_0}, \quad k_M=\omega\sqrt{\varepsilon_M\mu_0}, \quad k=\omega\sqrt{\varepsilon\mu_0} \tag{6}$$

whereJ_m $(m=0,\pm1,\pm2,\cdots)$ is the m-th order Bessel function, $H_m^{(1)}$ is the m-th order Hankel function of the first kind, p_m denotes the amplitude coefficient of the incident plane wave expressed by the cylindrical harmonic expansion. The first and second terms on the right hand side of Eq. (1) represent the incident and scattered waves, respectively. In Eqs. (1)–(3), **T**, **B**, **C**, and **D**are diagonal matrices which are given as follows:

$$\mathbf{T}=[T_m\delta_{mn}], \quad T_m=R_{12,m}+{\eta_M}^2{F_{12,m}}^2(1-R_{21,m}R_{23,m})^{-1}R_{23,m} \tag{7}$$

$$\mathbf{B}=[B_m\delta_{mn}], \quad B_m=(1-R_{21,m}R_{23,m})^{-1}F_{21,m} \tag{8}$$

$$\mathbf{C}=[C_m\delta_{mn}], \quad C_m=(1-R_{21,m}R_{23,m})^{-1}R_{23,m}F_{21,m} \tag{9}$$

$$\mathbf{D}=[D_m\delta_{mn}], \quad D_m=(1-R_{21,m}R_{23,m})^{-1}F_{32,m}F_{21,m} \tag{10}$$

with

$$R_{21,m}=-\frac{\eta_M H_m^{(1)}(u_M)H_m^{(1)\prime}(u_0)-H_m^{(1)\prime}(u_M)H_m^{(1)}(u_0)}{\eta_M J_m(u_M)H_m^{(1)\prime}(u_0)-J_m'(u_M)H_m^{(1)}(u_0)} \tag{11}$$

$$F_{12,m}=i\frac{2/(\pi\eta_M)}{[\eta_M J_m(u_M)H_m^{(1)\prime}(u_0)-J_m'(u_M)H_m^{(1)}(u_0)]} \tag{12}$$

$$R_{12,m}=-\frac{\eta_M J_m(u_M){J_m}'(u_0)-J_m'(u_M)J_m(u_0)}{\eta_M J_m(u_M)H_m^{(1)\prime}(u_0)-J_m'(u_M)H_m^{(1)}(u_0)} \tag{13}$$

$$F_{21,m}=\eta_M^2F_{12,m} \tag{14}$$

$$R_{23,m}=-\frac{\xi_M J_m(w_M)J_m'(w)-J_m'(w_M)J_m(w)}{\xi_M H_m^{(1)}(w_M)J_m'(w)-H_m^{(1)\prime}(w_M)J_m(w)} \tag{15}$$

$$F_{32,m}=-i\frac{2/(\pi\xi_M)}{\xi_M H_m^{(1)}(w_M)J_m'w)-H_m^{(1)\prime}(w_M)J_m(w)} \tag{16}$$

$$u_M=k_Mr_1, \quad u_0=k_0r_1, \quad w_M=k_Mr_2, \quad w=kr_2 \tag{17}$$

$$\eta_M=\sqrt{\varepsilon_M/\varepsilon_0}, \quad \xi_M=\sqrt{\varepsilon_M/\varepsilon} \tag{18}$$

where the matrix **T** given by Eq. (7) defines the T-matrix for the single coaxial cylinder.

For the two-cylinder system shown in Fig. 1(b), we have to take into account the multiple interactions of the fields scattered from individual cylinders. The interactions can be calculated by using