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Analysis of scattered field enhancement in the evanescent wave area based on the Discrete Sources Method

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ABSTRACT

In this paper the basic scheme of the Discrete Sources Method (DSM) has been modified to consider polarized light scattering by a non-spherical particle placed on a metal film deposited on a glass prism. The modified DSM model has been applied to examine the scattering properties of both metallic and dielectric particles. The Scattering Cross-Section enhancement versus particle diameter, refractive index, shape and height with respect to the film surface has been investigated. It has been demonstrated that it is possible to increase the corresponding scattered intensity by several orders choosing the appropriate shape of the gold particle and its height with respect to the film surface. Additionally, it has also been found that the DSC distribution in the incident plane shows narrow beams of the intensity directed inside a prism into the incident and specular directions.

1. Introduction

Surface plasmon (SP) excitation is known to contribute to exceptional optical properties of metal nanostructures. The excitation of SPs by light is denoted by a surface plasmon resonance (SPR) for planar surfaces or localized surface plasmon resonance for nanometer-sized metallic structures [1,2]. This phenomenon is of great potential application in nanophotonics, biophotonics, sensing, biochemistry and medicine [3]. In particular this phenomenon has been applied in developing optical antennas, biosensors, solar cells, transducers, nanolithography tools and OLEDs [4–8]. Typical metals that support SPs are silver and gold, but metals such as copper, titanium, or chromium can also support SP generation [9,10].

In order to design nanostructures with desired plasmonic properties, it is necessary to be able to simulate their optical response with high numerical accuracy. Application of computer simulation allows predicting the fundamental scattering properties of an entire system. Additionally, modeling of the nanostructures' properties and analyzing their light scattering behavior can be used for a correct interpretation of experimental data. For three-dimensional light scattering simulation, accurate modeling requires an appropriate choice of the specific numerical method. Since the most interesting nanoeffects are based on plasmonic resonances, the corresponding computer model must be based on a rigorous Maxwell theory.

Various numerical techniques have been used to this end. Finite Difference Time Domain (FDTD) [11] solves Maxwell's equations in the differential form in the time domain. FDTD is a simple technique, because it does not require profound knowledge of Maxwell theory. It is based on simple mathematical operations, which can be handled even by very simple computers. Unfortunately, these models are not accurate enough in some interesting cases in particular for plasmonic application [12]. Additionally, a conventional FDTD scheme does not account for an infinite plane interface and one has to apply special tricks to incorporate it [13].

Finite Element Method (FEM) [14] solves Maxwell's equations in the differential form in the frequency domain.

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The FEM implementation leads to matrix equations with large sparse matrices. The approach allows to obtain a very high numerical accuracy, which is important when simulating nanostructures that have not yet been fabricated. But direct application of the FEM to structures with plasmonic features can cause problems related to a truncation of the simulation domain [15]. Besides, FDTD and FEM have the disadvantage that they require both the scatterer and the background volume to be discretized, leading to higher computer demand.

Other common approaches are commonly known as semi-analytical methods. This means that Green′s theorem has to be applied to the system of Maxwell equations [16] to reduce the scattering problem formulated in the whole of 3D space to the impurity domain. There are volume-based methods, similar to Discrete Dipole Approximation (DDA) [17] and Volume Integral Equation (VIE) [18], which are suitable for modeling of light scattering by arbitrary impurities; and the surface based methods, such as T-matrix method [19], Surface Integral Equation (SIE) [20], Multiple MultiPole Technique (MMP) [21] and Discrete Sources Method (DSM) [22]. While volume-based methods can handle any kind of inhomogenities, they are pretty time consuming, especially if it is required to account for interaction between impurity and stratified interface. Surface-based methods seem to be more appropriate for the treatment of homogeneous features deposited near an interface. Most of them are direct methods. This means that they enables to solve a scattering problem for a whole set of the incident angles and polarizations at the same time. This is in contrast to DDA or VIE which require to start an iterative process for any new incident angle. Among the others, the MMP and the DSM have several advantages. First of all they are semi-analytical meshless methods that do not require any integration procedure. Besides, MMP and the DSM also provide a unique opportunity for a reliable validation of the results, as the errors of the solution can be calculated explicitly by evaluating the impurity surface residual [21,22].

As is known, diverse practical applications in nanoplasmonics require considering the simulation of scattering by features embedded in a stratified interface [6]. This leads to the necessity of accounting for multiple light reflections between a feature and the interface. The easiest way to handle this consists of incorporation of a Green Tensor (GT) of the stratified interface [23]. This can be easily done in the frame of semi-analytical methods only [17–25].

In this paper the basic scheme of the DSM is modified to consider non-spherical particle located at a gold film deposited upon a glass prism. Differential Scattering Cross-Section and Transmission and Reflection Cross-Sections are examined in details versus particle diameter, refractive index, shape and height with respect to the film surfaces. In particular it demonstrated that it is possible to increase the scattered intensity several orders by setting the shape of the particle and its height.

The theory of the DSM is considered in the next part of the paper and is followed by a short description of its numerical scheme. The computer simulation results based on the DSM model are presented and discussed in the last part of the paper.

2. DSM outlines

We consider a configuration consisting of a glass prism (half-space D_2, $z<0$), a metal film with a thickness d deposited on the prism (region D_1, $d>z>0$), and the other part of the space (D_0, $z>0$). We assume that the half-space D_0 contains a penetrable axially symmetric particle which internal domain is denoted by D_i (See Fig. 1). We will refer to the particle surface as ∂D_i. Let us choose a Cartesian coordinate system with its origin O on the prism surface and the Oz axis directed along the axis of symmetry of the particle. For external excitation, we consider a linearly polarized electromagnetic plane wave $\{\mathbf{E}^0,\mathbf{H}^0\}$ propagating from the prism at angle θ_2 to the Oz axis. Then mathematical statement of the scattering problem can be written in the following form:

$$
\begin{gathered}
\nabla\times\mathbf{H}_\zeta = jk\varepsilon_\zeta\mathbf{E}_\zeta;\quad \nabla\times\mathbf{E}_\zeta=-jk\mu_\zeta\mathbf{H}_\zeta \quad B \quad D_\zeta,\quad \zeta=0,1,2,i\\
\left.\begin{array}{l}\mathbf{n}_p\times(\mathbf{E}_i(p)-\mathbf{E}_0(p))=0,\\ \mathbf{n}_p\times(\mathbf{H}_i(p)-\mathbf{H}_0(p))=0,\end{array}\right. p\in\partial D_i,\qquad \left.\begin{array}{l}\mathbf{e}_z\times(\mathbf{E}_\alpha(p)-\mathbf{E}_\beta(p))=0,\\ \mathbf{e}_z\times(\mathbf{H}_\alpha(p)-\mathbf{H}_\beta(p))=0,\end{array}\right. p\in\ \Xi_{\alpha\beta},\\
\lim_{r\to\infty} \mathrm{r}\cdot\left(\sqrt{\varepsilon_\zeta}\mathbf{E}_\zeta\times\frac{\mathbf{r}}{r}-\sqrt{\mu_\zeta}\mathbf{H}_\zeta\right)=0,\quad r=|M|\to\infty,\ \zeta=0,2;\\
(|\mathbf{E}_1|,|\mathbf{H}_1|)=o(\exp\{-|\mathrm{Im}k_1|\rho\}),\quad \rho=\sqrt{x^2+y^2}\to\infty \qquad (1)
\end{gathered}
$$

here $\{\mathbf{E}_\zeta,\mathbf{H}_\zeta\}$ is the total field in the corresponding domain D_ζ, $k=\omega/c$, $\mathbf{n}_p$ is the outer unite normal vector to the particle surface ∂D_i, $\mathbf{e}_z$ is the unite basis vector of the Cartesian coordinate system directed along the Oz axis, $\Xi_{\alpha\beta}$, $\alpha,\beta=0,1,2$, is the interface plane separating domains D_α and D_β, $k_\alpha=k(\varepsilon_\alpha\mu_\alpha)$. We assume that the particle surface ∂D_i is smooth enough and that the p arameters of the media satisfy the following conditions $\mathrm{Im}\varepsilon_\zeta,\mu_\zeta\leq 0$, which correspond to the time dependence – $\exp\{j\omega t\}$. Then, the boundary scattering problem (1) has a unique solution.

Let us first solve the problem of reflection and transmission of the plane wave $\{\mathbf{E}^0,\mathbf{H}^0\}$ at the plane-layered interface. This can be done analytically to obtain the external excitation field $\{\mathbf{E}^0_\zeta,\ \mathbf{H}^0_\zeta\}$ in each domain D_ζ, $\zeta=0,1,2$. This field satisfies the transmission conditions enforced at planes ($z=0,d$) and the corresponding infinity conditions. Then we define the scattered field in each D_ζ, $\zeta=0,1,2$ as $\mathbf{E}^s_\zeta=\mathbf{E}_\zeta-\mathbf{E}^0_\zeta,\mathbf{H}^s_\zeta=\mathbf{H}_\zeta-\mathbf{H}^0_\zeta$. The scattered field should satisfy the infinity conditions and the transmission

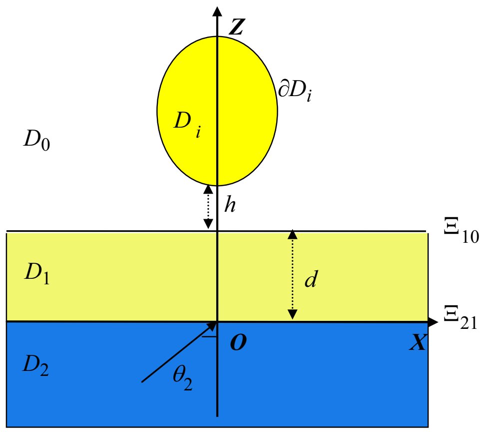

Fig. 1. Scattering problem geometry.