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Extreme Scattering Effect: Light scattering analysis via the Discrete Sources Method

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ABSTRACT

The effect of the Extraordinary Optical Transmission (Ebbesen et al. Nature 1998; 391, 667) through subwavelength holes array in noble metal screen is used for multiple practical applications in nanooptics and biophotonics. In this paper the Extreme Transmission Effect (Eremina et al. Opt. Comm. 2008; 281, 3581) in the noble metal film deposited on a glass prism in the evanescent wave's area is in focus. The Discrete Sources Method (DSM) has been adjusted to calculate the polarized light scattering by an axially symmetric inclusion located in a film deposited on a glass prism. We extended the DSM for the evaluation of the Scattering Cross-Section in the prism domain. It has been shown that the maximum value of the Reflection Cross-Section appears at the same incident angle as for the Transmission Cross-Section. It has been demonstrated that the Reflection Cross-Section can exceed the Transmission Cross-Section under certain circumstances. Analysis of the correlation between the Plasmon Resonance in the gold film and the Extreme Scattering Effect demonstrates that the Plasmon Resonance plays an important but not the exclusive role in the appearance of the Extreme Scattering Effect.

1. Introduction

Since the effect of Extraordinary Optical Transmission through arrays of subwavelength holes in metal screens has been detected by Ebbesen et al. [1] it attracted considerable interest by numerous research groups. The ability to localize light in spots much smaller than the volume predicted by diffraction theory offers multiple practical applications in nanooptics and biophotonics. In the paper of Wannemacher [2] this effect has been explained by plasmons excitation. It is now generally agreed that Plasmon Resonance plays a key role in the enhancement of the light transmission through subwavelength apertures in noble metal screens [3–9]. Recently different scientific teams worldwide have examined the transmission properties of subwavelength apertures in connection with the development of multiple practical applications in nanooptics [10–15].

In our recent paper [16] the effect of extreme light transmission through a nanohole in a noble metal film on a glass prism surface has been reported. The Extreme Transmission Effect differs from the Extraordinary Optical Transmission. The main differences are that it appears in the evanescent wave area only; the Transmission Cross-Section (TCS) connected to the Extreme Transmission Effect under certain "optimal incident angle" beyond the critical one exceeds at an order the TCS under normal excitation, which is usually used in connection with Extraordinary Optical Transmission; besides, the TCS in the Extreme Transmission Effect is extremely sensitive to the change

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of the incident angle and varies up to two orders under variation in the incident angle by just 1.5°. It was found that the Extreme Transmission Effect itself does not depend on the metal film's thickness, hole's diameter and its filling, but it is strongly influenced by the metal film material. In the consecutive papers it was found that the Extreme Transmission Effect occurs not only for hole but also for other types of the film inhomogeneities [17–19].

For three-dimensional light scattering simulation accurate modeling requires an appropriate choice of the method. Since the most interesting nanoeffects are based on resonances, the corresponding computer model must be based on rigorous Maxwell theory. There are multiple approaches, which have been applied to light scattering analysis: Finite Difference Time Domain (FDTD) [20], Finite Element Method (FEM) [21], Coupled Dipole Approximation [22], Volume Integral Equation (VIE) [23], Multiple MultiPole Technique (MMP) [24], Null Field Method [25] and Discrete Sources Method (DSM) [26]. However, most of these methods have different characteristics, restrictions and advantages. The advantage of pure numerical methods, such as the FDTD or the FEM, is the simplicity of implementation. They are applied directly to Maxwell equations. There was a strong trend toward FDTD solvers in the last decades. FDTD is a simple technique, because it does not require profound knowledge of the Maxwell theory. It is based on simple mathematical operations, which can be handled even by very simple computers. Time domain formulations have big advantages when non-linear materials are present, but they are not really well suited for dispersive materials with strong nonlinearities in their frequency response. These models are not accurate enough in many cases [27]. In addition, a conventional FDTD scheme does not account for infinite plane interfaces or uses special trick to approximate it [28]. The simplest way to get rid of problems connected with materials dispersion or strong skin effects near the metal films is to work in the frequency domain. This approach leads to direct methods, such as the FEM. The FEM implementation leads to matrix equations with large sparse matrices. The approach allows to reach a very high accuracy, which is valuable when one explores nanostructures that have not been fabricated yet. However direct application of the FEM to structures with plasmonic features can cause problems related to the truncation of the simulation domain [29].

Other approaches mentioned above are commonly known as semi-analytical methods. This means that one has already applied the Green theorem to the system of Maxwell equations and reduced the scattering problem formulated in whole 3D space to the impurity domain. These methods can be divided into two categories: the volume based methods similar to DDA [30] and VIE, which are suitable for modeling of light scattering by arbitrary impurities, and the surface based methods like MMP, Null Field Method and DSM. While volume based methods can handle any kind of inhomogeneities, they are pretty time consuming, especially for the evaluation of integrated scattering characteristics. Surface based methods seem to be more appropriate for the examination of homogeneous features deposited near an interface. Among others, the MMP and the DSM have several advantages. First of all they are semi-analytical meshless methods, which do not require any integration procedure. The MMP and the DSM also provide a unique opportunity for a reliable validation of the results, as the errors can be calculated explicitly.

In this paper we adjusted the DSM to analyze polarized light scattering by an inclusion located in a noble metal film deposited on a glass prism. The DSM was extended to evaluate first the Differential Scattering Cross-Section and the Reflection Cross-Section (RCS) in the prism domain. The theory of the method is presented in the next part of the paper and is followed by the description of the DSM numerical scheme. The numerical results based on the DSM model are presented and discussed in the last part of the paper.

2. DSM scattering model

In this section the DSM outlines are discussed. Assume that the whole space is divided into three domains: air D_0, film D_f and the glass prism, which is represented as a half-space D_1. Let the plane Σ_1 separate the film and the prism and the plane Σ_f separates air and the film. An axially symmetric inclusion occupying a certain domain D_i with a smooth boundary ∂D is located inside the film of thickness d, bounded by the planes Σ_1 and Σ_f. We assume that the symmetry axis of the inclusion coincides with the normal direction to Σ_1. Now we introduce a Cartesian coordinate system $Oxyz$ by choosing its origin O at the prism surface Σ_1. Let the Oz axis coincide with the symmetry axis of the inclusion and is directed to D_0. The plane $z=0$ corresponds to the Σ_1 plane (Fig. 1).

Then the mathematical statement of the scattering problem for the scattering field outside D_i and the total field inside D_i can be formulated in the following form:

$$\nabla \mathbf{H}_\zeta = jk\varepsilon_\zeta \mathbf{E}_\zeta; \quad \nabla \mathbf{E}_\zeta = -jk\mu_\zeta \mathbf{H}_\zeta \text{ in } D_\zeta, \quad \zeta = 0,1,f,i$$

$$\begin{aligned} \mathbf{n}_p(\mathbf{E}_i(p)-\mathbf{E}_f^s(p)) &= \mathbf{n}_p\mathbf{E}_f^0(p), \\ \mathbf{n}_p(\mathbf{H}_i(p)-\mathbf{H}_f^s(p)) &= \mathbf{n}_p\mathbf{H}_f^0(p), \end{aligned} \quad p \in \partial D \tag{1}$$

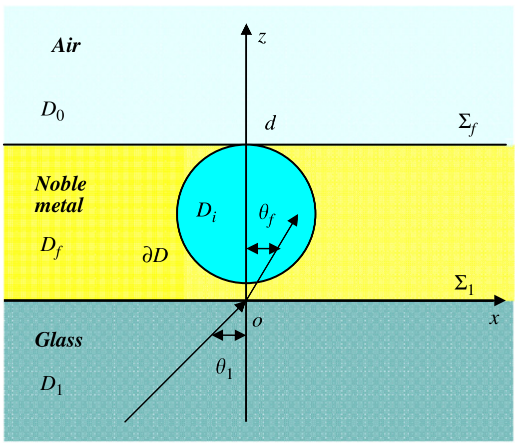

Fig. 1. Model geometry.