Available online at www.sciencedirect.com
ScienceDirect
Optics Communications 281 (2008) 3581–3586
Optics Communications
www.elsevier.com/locate/optcom

Analysis of light scattering in the evanescent waves area by a cylindrical nanohole in a noble-metal film

Elena Eremina [a,*], Yuri Eremin [b,1], Natalia Grishina [b,1], Thomas Wriedt [c,2]

[a] Universitaet Bremen, Badgasteiner Street 3, 28359 Bremen, Germany
[b] Moscow Lomonosov State University, Lenin's Hills, 119991 Moscow, Russia
[c] Institut für Werkstofftechnik, Badgasteiner Street 3, 28359 Bremen, Germany

Received 11 December 2007; received in revised form 7 March 2008; accepted 11 March 2008

Abstract

The discrete sources method has been extended to analyze the scattering behavior of a cylindrical nanohole in a noble-metal film deposited on a glass prism. The dependence of the transmitted intensity on the incident angle has been investigated. Extreme transmission of the incident plane wave has been detected in the evanescent waves area.

Keywords: Evanescent wave; Nanohole; Extreme transmission; Discrete sources method

1. Introduction

The discovery of enhanced optical transmission through a subwavelength hole has attracted considerable interest to this optical phenomena and applications associated with nanoscale apertures in metal films [1]. The ability to localize light in spots much smaller than the volume predicted by diffraction theory offers multiple applications in biophotonics, such as probing a few molecules in a highly concentrated solution or monitoring a cell membrane with a submicrometer resolution [2,3]. Combination of a hole with other surface nanostructures or using nanohole arrays offers a wide variety of potential applications as well [4].

It is generally agreed that surface plasmon resonances play a key role in enhancing of light transmission through apertures in noble metal films [5,6]. Different groups worldwide have recently examined the transmission properties of sub-wavelength apertures. In particular, Wannemacher [1] has studied the fundamental characteristics of a single circular nanohole in thin conducting films, as well as the role played by surface plasmon polaritons in the transmission process. Sönnichsen et al. [6] detected locally excited surface plasmons in a metal film by investigating transmission through a single nanohole using scanning near-field optical microscopy (SNOM). de Abajo [7,8] has examined light transmission through simple circular holes in perfectly conducting and real metal films, and holes containing additional structure such as a sphere or a high index dielectric filling, which seems to improve the transmission efficiency at specific wavelengths. Shuford et al. [9] have been investigating the effect of a substrate influence on the transmission properties. Degiron et al. [10] have shown that real metal plays a key role to support light transmission in a nanohole. The effect of *P*-polarized transmission efficiency has been considered by Eom et al. [11]. In the paper of Yin et al. [12] the final difference time domain (FDTD) has been used to model the problem and simulation results have been compared to experimental ones. More information regarding the transmission problem can be found in recent reviews [5,7].

In most papers mentioned above normal incidence is used as an external excitation. At the same time, there

* Corresponding author. Tel.: +49 421 218 3583; fax: +49 421 218 5378.
E-mail addresses: eremina@iwt.uni-bremen.de (E. Eremina), eremin@cs.msu.su (Y. Eremin), thw@iwt.uni-bremen.de (T. Wriedt).
1 Tel./fax: +7 095 939 1776.
2 Tel.: +49 421 218 3583; fax: +49 421 218 2507.

0030-4018/$ - see front matter
doi:10.1016/j.optcom.2008.03.039

are multiple practical applications using an evanescent wave as external excitation [13,14]. Employing evanescent waves may allow to avoid the problem of filtering the scattered light from the refracted one. In this paper, we consider the evanescent wave scattering properties of a single sub-wavelength hole in a noble-metal film filled by a dielectric medium. The discrete sources method (DSM) [15] has already been applied to model light scattering by different nanoobjects on a plane surface [14,16]. In this paper, the DSM is adjusted to model evanescent light scattering of a fixed wavelength by a nanohole. The influence of the incident angle on the scattering properties of the hole is investigated. The effects of the size and filling of the hole, as well as the material and thickness of the metal film are considered.

In the next chapter, we present the theoretical outlines of the DSM. In the third chapter the numerical algorithm is presented and computer simulation results are discussed in the last chapter of the paper.

2. Mathematical model

Let an axially symmetric hole occupying a certain domain D_i with a smooth boundary ∂D be situated inside a film of thickness d, which is bounded by the planes Σ_1 and Σ_f. The plane Σ_1 separates the film and the substrate (glass prism). We denote the prism domain by D_1 and ambient space exterior to the film and the hole by D_0. The upper half-space D_0 and the interior of the hole D_i are filled with water. Let us introduce a Cartesian coordinate system Oxyz by choosing its origin O at the prism-surface Σ_1 in the center of the hole and O_z axis is directed into domain D_0. The plane $z = 0$ corresponds to the Σ_1 plane (Fig. 1). We assume that the exciting field $\{\mathbf{E}^0, \mathbf{H}^0\}$ is a plane wave propagating from D_1 at the angle θ_1 with respect to the z-axis.

Then the mathematical statement of the scattering problem can be formulated as follows:

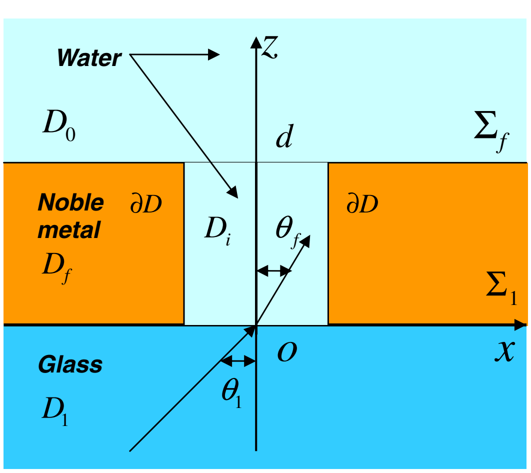

Fig. 1. Model geometry.

$$
\begin{aligned}
&\nabla \times \mathbf{H}_\zeta = jk\varepsilon_\zeta \mathbf{E}_\zeta;\ \nabla \times \mathbf{E}_\zeta = -jk\mu_\zeta \mathbf{H}_\zeta \text{ in } D_\zeta,\\
&\qquad \zeta = 0, 1, f, i,\\
&\left.\begin{aligned}&\mathbf{n}_p \times (\mathbf{E}_i(p) - \mathbf{E}_f(p)) = 0,\\ &\mathbf{n}_p \times (\mathbf{H}_i(p) - \mathbf{H}_f(p)) = 0,\end{aligned}\right. \quad p \in \partial D;\\
&\left.\begin{aligned}&\mathbf{e}_z \times (\mathbf{E}_f(p) - \mathbf{E}_1(p)) = 0,\\ &\mathbf{e}_z \times (\mathbf{H}_f(p) - \mathbf{H}_1(p)) = 0,\end{aligned}\right. \quad p \in \sum_1;\\
&\left.\begin{aligned}&\mathbf{e}_z \times (\mathbf{E}_0(p) - \mathbf{E}_f(p)) = 0,\\ &\mathbf{e}_z \times (\mathbf{H}_0(p) - \mathbf{H}_f(p)) = 0,\end{aligned}\right. \quad p \in \sum_f
\end{aligned}
\tag{1}
$$

and radiation/attenuation conditions at infinity for the scattered field at $z \neq 0,d$.

Here, $\mathbf{e}_z$ is the unit normal vector to the surfaces $\Sigma_{1,f}$, $\mathbf{n}_p$ is the outward unit normal vector to ∂D, $k = \omega/c$ and $\{\mathbf{E}_\zeta,\mathbf{H}_\zeta\}$ stands for the total field in the corresponding domain D_ζ, $\zeta = 0,1,f,i$. While in $D_{1,f}$ the total field consists of incident and reflected waves, in D_0 the total field includes the transmitted wave which transforms to the evanescent one under certain conditions. If $\operatorname{Im}\varepsilon_\zeta$, $\mu_\zeta \leqslant 0$ (the time dependence for the fields is chosen as $\exp\{j\omega t\}$) and the particle surface is smooth enough: $\partial D \subset C^{(2,\alpha)}$, then the above boundary-value scattering problem is uniquely solvable [17].

We construct an approximate solution to the scattering problem (1) based on the DSM [14]. First, the plane wave $\{\mathbf{E}^0,\mathbf{H}^0\}$ scattering problem on the interface is solved. The result yields external excitation fields $\{\mathbf{E}^0_\zeta, \mathbf{H}^0_\zeta\}, \zeta = 0, 1$ in domains $D_{0,1}$, which satisfy the transmission conditions at the plane interface. Let us construct the approximate solution of the boundary value problem (1) for the scattered field $\{\mathbf{E}^s_\zeta, \mathbf{H}^s_\zeta\}$ in D_ς, $\zeta = 0,f,1$ and the total field in D_i.

In the frame of DSM [15] the approximate solution is constructed by representing the electromagnetic fields as a finite linear combination of the electric and magnetic fields of multipoles distributed over an axis of symmetry inside the scatterer. Besides, the fields analytically satisfy the transmission conditions enforced at the plane interfaces $\Sigma_{1,f}$, which provides an opportunity to account for whole interactions between scatterer and interface. Then the approximate solution satisfies Maxwell equations in the domains D_ζ, $\zeta = 0, 1, f, i$, the infinity conditions and the transmission conditions at plane interfaces $\Sigma_{1,f}$. Thus, the scattering problem is reduced to the problem of approximation of the exciting field on the hole surface ∂D. Only the amplitudes of the discrete sources (DS) are to be determined from the boundary conditions at ∂D. Which can be rewritten in the following form

$$\mathbf{n}_p \times (\mathbf{E}_i - \mathbf{E}^s_f) = \mathbf{n}_p \times \mathbf{E}^0_f \quad \mathbf{n}_p \times (\mathbf{H}_i - \mathbf{H}^s_f) = \mathbf{n}_p \times \mathbf{H}^0_f. \tag{2}$$

Prior to the construction of an approximate solution for the scattered field, the plane wave diffraction problem on the layered structure must be solved. The field representation can be written as

$$\mathbf{E}^{P,S}_f = W^{P,S}_i \mathbf{E}^+_f + W^{P,S}_r \mathbf{E}^-_f, \quad \mathbf{H}^{P,S}_f = W^{P,S}_i \mathbf{H}^+_f + W^{P,S}_r \mathbf{H}^-_f. \tag{3}$$