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3D vector distribution of the electro-magnetic fields on a random gold film

Damien Canneson [a,*], Bruno Berini [a], Stéphanie Buil [a], Jean-Pierre Hermier [a,b], Xavier Quélin [a,**]

[a] Université de Versailles Saint-Quentin, Groupe d'Etude de la Matière Condensée (GEMaC), CNRS UMR8635, Université Paris-Saclay, 45 avenue des Etats-Unis, 78035 Versailles cedex, France

[b] Institut Universitaire de France, 103 Bd Saint-Michel, 75005 Paris, France

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ABSTRACT

The 3D vector distribution of the electro-magnetic fields at the very close vicinity of the surface of a random gold film is studied. Such films are well known for their properties of light confinement and large fluctuations of local density of optical states. Using Finite-Difference Time-Domain simulations, we show that it is possible to determine the local orientation of the electro-magnetic fields. This allows us to obtain a complete characterization of the fields. Large fluctuations of their amplitude are observed as previously shown. Here, we demonstrate large variations of their direction depending both on the position on the random gold film, and on the distance to it. Such characterization could be useful for a better understanding of applications like the coupling of point-like dipoles to such films.

1. Introduction

Since the early nineties, many theoretical [1–3] and experimental [4–6] studies have been performed on the striking electromagnetic (EM) properties exhibited by random metal films. Most of these works concerned semi-continuous gold or silver layers. Such systems are usually obtained by depositing a small amount of metal onto a dielectric substrate and can be described as an assembly of nanoparticles with random shapes, sizes and locations. Very intense fields induced by light, randomly dispersed, confined on a few nanometers and arising over a broad spectral range [7] are linked to the disordered nature of these films. These strongly confined fields are called "Hot Spots" (HS) and have been associated to Surface Plasmon Resonance (SPR) with both localized and delocalized modes [8]. Numerous experimental studies [9–11] have mapped localized intensity maxima on such metal films. The dependencies on the incident wavelength or incident polarization state have also been underlined [12]. More recently, those dependencies have also been evidenced using four-wave mixing experiments [13].

More recently, considering a single point-like dipole deposited on a random metal surface, the decay processes (radiative or not) and the intensity enhancement of the photoluminescence have been studied in numerous papers [14–23]. But, for all these studies [9–23], the vector nature of the interaction between the dipole moment and the local electromagnetic field is hidden. The full-vector nature of the EM fields involved in the HS is not considered. Either because the point-like dipole probing the HS distribution is not defined (fluorescent beads [20]) or not characterized (semiconductor nanocrystals [14–18]); or because the experimental technique used addresses only one component of the local EM field (the normal component respective to the film for Scanning Tunneling Electron Microscopy-Electron Energy Loss Spectroscopy (STEM-EELS) for example [23]).

It has been also demonstrated that the Finite-Difference Time-Domain (FDTD) technique [24,25] is an appropriate and powerful tool to characterize the intensity enhancements on disordered metal films [26–28] and to give a 2D-vectorial description of the induced fields on simple plasmonic structures [29–31].

In this paper we show that, using the numerical FDTD method, it is possible to give a description of the full 3D-vector EM fields on random metal films. A semi-continuous gold layer, deposited on a glass substrate (xy plane), is studied. First, we check a previous experimental result [10] that was already confirmed numerically by FDTD method [28]: the spatial distribution of the near-field intensity exhibits large fluctuations. Then, on specific reduced zones, we present the evolution of the 3D EM fields with the z distance and the incident wavelength. The presented results clearly show that the direction, as the amplitude, of the EM fields is strongly fluctuating on the gold surface.

* Correspondence to: Experimentelle Physik 2, Technische Universität Dortmund, Otto-Hahn-Straße 4a, D-44227 Dortmund, Germany.
** Corresponding author.
E-mail addresses: damien.canneson@tu-dortmund.de (D. Canneson), xavier.quelin@uvsq.fr (X. Quélin).

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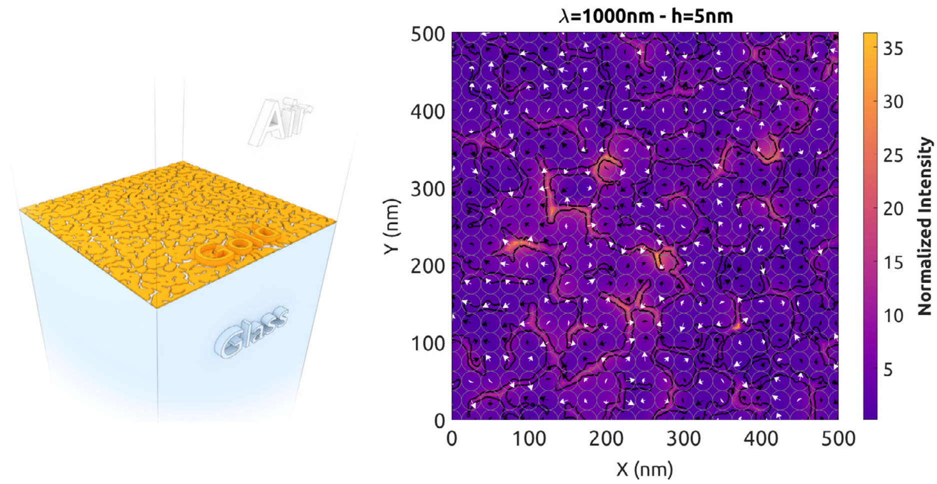

Fig. 1. (left) Artist view of the real 3D, AFM measured, gold film surface deposited on a glass substrate and (right) EM field distribution for an excitation wavelength $\lambda = 1000$ nm and at a distance $h = 5$ nm above the gold surface. The color filling represents the EM intensity and the arrows, the EM field direction (more detailed explanations in text and on Fig. 2). As can be seen on this quite large area (500×500 nm^2), the direction of the EM local fields is very inhomogeneous, differing drastically from the incident excitation (along x direction). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

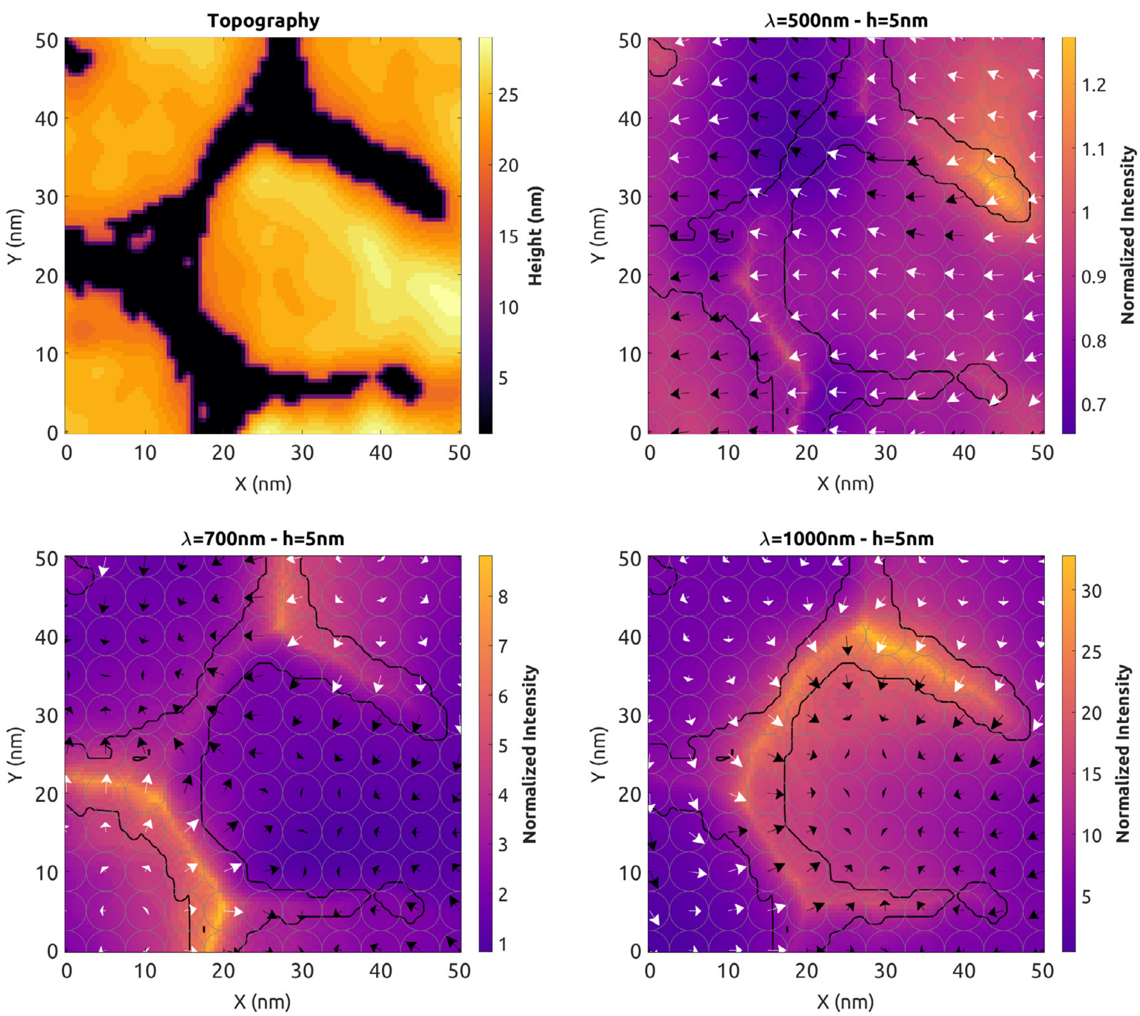

Fig. 2. 3D distribution of the EM fields on a reduced (50×50 nm^2) area. The excitation wavelengths are $\lambda = 500$ nm (top right), $\lambda = 700$ nm (bottom left) and $\lambda = 1000$ nm (bottom right). The distance to the surface is $h = 5$ nm. The image at the top left shows the topography of this area. The color filling represents the EM intensity with respect to the color bar associated with each sub-figure. The arrows represent the vector components of the EM field (its direction). All the arrows are normalized, i.e. whatever the intensity is, the length of the arrow is only associated to the direction of the EM field. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)