Iterative Image Method for Apertureless THz Near-field Microscope

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***Abstract*—We propose a self-consistent calculation method for apertureless THz near-field microscope (NFM) which is based on an exact image theory. Within the quasi-electrostatic limit, the exact image theory was iteratively applied to calculate interactions between dielectric spheres and substrate effects. The calculated near field was in excellent agreement with results from a commercial finite element method (FEM) simulator.**

I. Introduction

Recently terahertz (THz) technology has been attracting a lot of attention for various applications such as THz imaging and characterization of materials and devices by THz time-domain spectroscopy (THz TDS)[1]. THz TDS provides a powerful means to probe the electronic and optical properties of both semiconductor and biomolecular nanostructures. However the spatial resolutions of conventional THz TDS systems are limited by diffraction. THz apertureless near-field microscopy (NFM) combines THz TDS with atomic force microscopy (AFM) techniques to overcome the diffraction limit. THz NFM provides THz spectral imaging as well as topography of a sample surface[2-5].

In the conventional model for NFM, both the probe tip and the sample nanoparticle are represented by small polarizable dielectric spheres[6], and adopted a simple image theory to calculate the interaction between the probe tip and the sample sphere. However, the method is not self-consistent since the interactions between spheres and the substrate effect are not fully taken into account. Recently, a self-consistent analytic scattering theory for apertureless NFM which is based on an exact image theory has been reported[7]. However, it was applicable to one dielectric sphere on substrate.

In this paper, as an extension of the previous theory, we propose a self-consistent semi-analytic scattering theory which is applicable to arbitrary numbers of particles on a substrate.

II. Theory and Results

A. Theory

Suppose that there are two dielectric spheres each representing the tip and the sample nano-particle on a dielectric substrate, and an electric field is applied. If the spheres are located in close proximity to each other, then the simple dipole approximation does not give accurate results. Therefore, to calculate the scattered near-field of the THz NFM system, an alternative method is needed.

Ignoring the interactions between the spheres, the induced image dipole at the centers of a sphere by applied electric field $\vec{E}_0 = E_0\hat{u}$ is calculated by:

$$\bar{p}_0 = \hat{u}4\pi\varepsilon_0 a^3 \frac{\varepsilon_a - 1}{\varepsilon_a + 2} E_0 \tag{1}$$

where a and ε_a represent the radius and the permittivity of the sphere, respectively. The induced image dipoles of the isolated spheres can be taken as zeroth-order terms for the iteration. The problem of a point dipole in front of a dielectric sphere was exactly solved by applying an image theory[8-9]. Therefore, the first-order image dipoles induced by the zeroth-order image dipoles can be calculated by adopting the exact image method by assuming the zeroth-order image dipoles as external dipole sources. The image dipoles induced in the substrate is calculated by the simple image theory for dielectric interfaces[10]. The second-order image dipoles can be calculated from the first-order image dipoles exactly in the same manner. By applying the exact image method iteratively until the total induced dipole moment converges to a certain value, the complete dipole distribution which reflects existing interactions between the two spheres and the substrate can be obtained. The near-field profile can then be calculated from the calculated dipole distribution. The procedure is schematically shown in Fig.1.

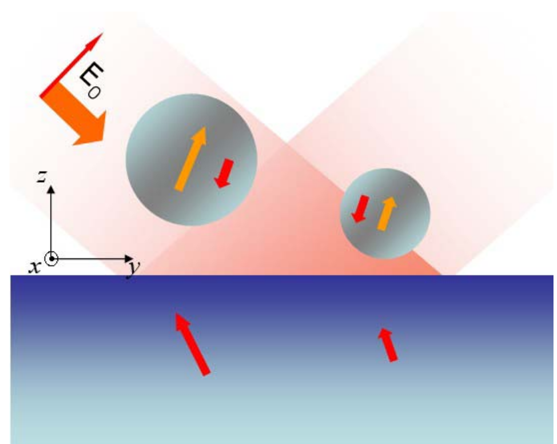

Fig. 1. Orange arrows represent 0th order dipole moments which are induced by the total external field. Red arrows represent 1st order dipole moments which are induced by 0th order dipole moments.

B. Results

The scattered near-field for THz NFM system has been calculated using iterative image method and HFSS, a commercial software based on the finite element method. The tungsten tip and the GaAs particle were approximated by dielectric spheres with diameter of 40 nm, and effects of the Au substrate were also included. The electric field polarized in the y-z plane is incident on the nanospheres with an incidence angle θ_{in} =60°.

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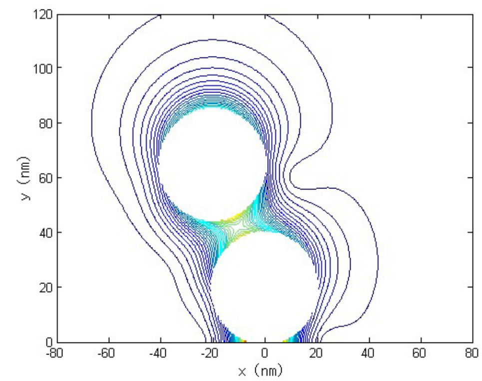
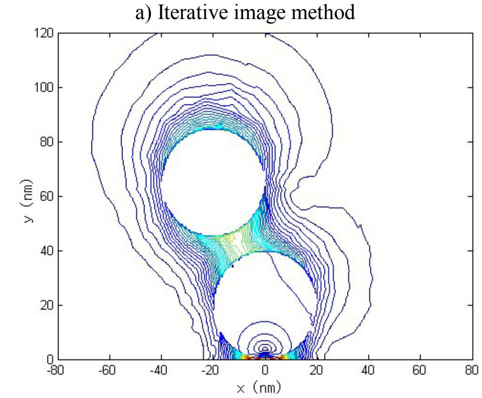
The scattered near-field distribution calculated using the iterative image method is shown in Fig.2. As expected, the THz near-field is strongly localized at the tip-to-sample gap by the interaction between the tip and the sample. The semi-analytic result from our self-consistent theory is in excellent agreement with the result from HFSS.



a) Iterative image method



b) Commercial FEM tool (*HFSS*).

Fig. 2. The calculated near-field profiles for W and GaAs nano-spheres on an Au substrate.

III. CONCLUSION

In summary, we have proposed a self-consistent iterative image theory for the apertureless THz NFM. The semi-analytic iteration method based on the exact image theory is equally applicable to other scattering problems with arbitrary numbers of nanospheres on a substrate.

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