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Image dipole approach and polarization effects in scanning near-field optical microscopy

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Abstract

A coupled-dipole approach is proposed in order to study the coupling between the probe tip and the rough sample in SNOM. In the present model both the optical probe tip and the sample protrusions are represented by polarizable dipole spheres. The induced polarization effects on the sample surface can be replaced by the image dipoles in the circumstance of quasi-static electromagnetic field approximation. Applying the radiation theory of the dipole, we have established a set of self-consistent equations to describe the field distribution at the sites of the probe tip and the sample protrusions. The results are completely the same as those obtained by means of the dyadic electromagnetic propagator formalism and also the derivation procedure is relatively simple. This method permits us to analyze the physical mechanisms of the interaction between the probe tip and the rough surface in SNOM intuitively. Based on this approach, we further discuss the influence of polarization of the incident light on the imaging quality. The calculating result shows that the shape and the contrast of the images of the sample are both sensitive to the field polarization, and the z-polarized mode is proved to give better resolution in SNOM.

Keywords: Scanning near-field optical microscopy; Quasi-static electromagnetic field; Image dipole

1. Introduction

The theoretical study of scanning near-field optical microscopy (SNOM) plays an important role in the near-field optical technology. There mainly exist two methods, one is a numerical calculation and the other theoretical analysis. The finite-difference time-domain calculation is a widely used numerical method [1], but the problem concerning the choice of suitable electromagnetic boundary conditions in SNOM remains unsolved, which confines its further application. The rigorous theoretical analyses using field propagator formalism to investigate the SNOM had been first reported by Girard et al. [2,3]. Subsequently, Keller et al. extended this method and proposed the concept of the direct near-field propagator and indirect near-field propagator [4–6]. Girard and Keller et al. all adopted field-susceptibility Green's-function technique and applied an integral-equation formalism to overcome obstacles inherent in the matching of the electromagnetic boundary conditions on the sample surface. Through a complicated derivation, they obtained the exact analytical expression of the field propagator and solution of the complete field distribution. This complexity of calculation prevents us from understanding the physical mechanisms of the interaction between the probe tip and the surface in SNOM. In this paper, we

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developed a new theoretical method of investigating the main features of the physical interaction between a probe tip and a corrugated surface in SNOM. Instead of directly solving the field solution to the system, we prefer an indirect way in which the equivalent effect principle is applied to avoid the calculating complexity stemming from the boundary condition. The validity of this method is verified compared with the former theoretical result. The principal advantage of this approach lies in its practicality and simplicity in calculation. Furthermore, we discuss the influence that the polarization of the incident light has on the imaging quality of the SNOM.

2. Image dipole model

The framework of the model is the polarizable dipole representation of both the sample protrusions and the probe tip, and the induced dipole moment in these small particles is proportional to the local field in the dipole's position. This model is justified in calculating the response of the nanometric objects to the incident field [7]. The system to be considered in this paper is shown in Fig. 1. The collecting probe tip characterized by a dynamical polarizability α_t with radius a is placed in front of a surface at a distance R_t, and all similar sample protrusions by polarizability α_s with radius b are placed between the probe tip and the surface at a distance R_s from the surface. The bulk sample with relative complex dielectric constant ε occupies half-space $z>0$.

If the boundary condition of the system can be obtained exactly, one can apply Green's-function technique to derive the whole field distribution. But owing to the existence of the polarization effects on the sample surface induced by the probe tip dipole and the sample dipoles, the field distribution on the sample surface is difficult to determine. In order to overcome this obstacle, we adopted the quasi-static electromagnetic field theory in which these screening effects take the place of image dipoles. This treatment is based on the consideration of the approach distance R_t quite small with respect to the wavelength associated with the excitation field. In case of incident light $\boldsymbol{E}$ perpendicular

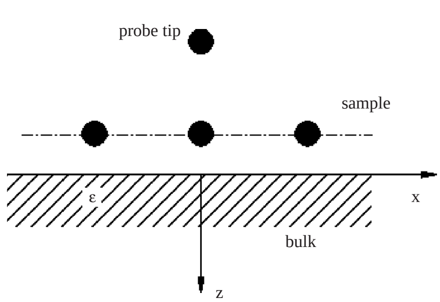

Fig. 1. Schematic diagram showing the geometry of system, i.e. the probe tip sphere, the sample in SNOM.

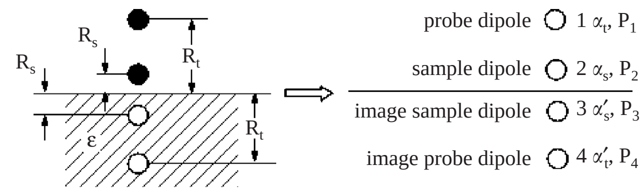

Fig. 2. Schematic diagram showing the image dipole model for SNOM, i.e. the probe tip dipole, the sample dipole and their image dipoles.

to the sample surface (z polarization direction), this screening effect on the sample surface caused by a dipole with dipole moment $\boldsymbol{p}$ at a distance R can be replaced by an image dipole with dipole moment $\boldsymbol{p}'$ located inside the bulk sample at a distance $2R$ from the real dipole, as shown in Fig. 2 [8],

$$\boldsymbol{p}' = \beta \boldsymbol{p}, \tag{1}$$

where $\beta = (\varepsilon - 1)/(\varepsilon + 1)$. For the case of incident light $\boldsymbol{E}$ parallel to the sample surface (including x and y polarization directions), the effective dipole moment of the image dipole becomes

$$\boldsymbol{p}' = -\beta \boldsymbol{p}. \tag{2}$$

We now examine the radiation field distribution of the dipole. The total electric and magnetic fields from a dipole with dipole moment $\boldsymbol{p}$ are as follows [9]:

$$\begin{aligned}\boldsymbol{E}(\omega, \boldsymbol{r}) = {} & \frac{1}{4\pi\varepsilon_0} \exp(\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r} - \mathrm{i}\omega t) \\ & \times \left\{ \frac{1}{r^3}[3\hat{\boldsymbol{r}}(\hat{\boldsymbol{r}}\cdot\boldsymbol{p}) - \boldsymbol{p}] \right. \\ & \left. - \frac{\mathrm{i}k}{r^2}[3\hat{\boldsymbol{r}}(\hat{\boldsymbol{r}}\cdot\boldsymbol{p} - \boldsymbol{p})] - \frac{k^2}{r}[\hat{\boldsymbol{r}} \times (\hat{\boldsymbol{r}} \times \boldsymbol{p})] \right\},\end{aligned} \tag{3}$$

$$\boldsymbol{H}(\omega, r) = -\frac{\mathrm{i}\omega}{4\pi\varepsilon_0} \exp(\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r} - \mathrm{i}\omega t)\left(\frac{1}{r^2} - \frac{\mathrm{i}k}{r}\right)\boldsymbol{p} \times \hat{\boldsymbol{r}}, \tag{4}$$

where $\hat{\boldsymbol{r}}$ is the unit vector along the $\boldsymbol{r}$ direction. In the far field ($kr \gg 1$), $1/r$ terms dominate; these are the radiation terms. In the near field ($kr \ll 1$), $1/r^3$ terms dominate; these are the evanescent terms. In the near-field region, the ratio of electric energy density to magnetic energy density is

$$\frac{U_E(r)}{U_H(r)} = \frac{\varepsilon_0 |E|^2}{\mu_0 |H|^2} \approx \frac{1}{k^2 r^2} \gg 1. \tag{5}$$

As can be seen, in our concerning near-field region, this ratio is much greater than 1, so in the following, we keep only the near-field electric contribution proportional to $1/r^3$ in Eq. (3).

Based on the analysis above, we can obtain a set of equations describing the field distribution of the system as shown in Fig. 2. This calculation must be performed self-consistently, since the local field seen from one dipole depends upon the fields seen from all the others