COMPUTER SIMULATION FOR 2-DIMENSIONAL SCANNING NEAR-FIELD OPTICAL MICROSCOPE

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1. Introduction

It has been reported that the Scanning Near-field Optical Microscope (SNOM) can detect objects with the very high resolution, where the images are beyond the refraction limit [1,2]. In order to investigate this physical phenomenon, it is very important subject to develop an accurate simulator of the SNOM. In this paper, we propose the new type of boundary integral equations for 2-dimensional SNOM (2D-SNOM), which can be solved with high accuracy by using the conventional moment method (MoM) [3-5].

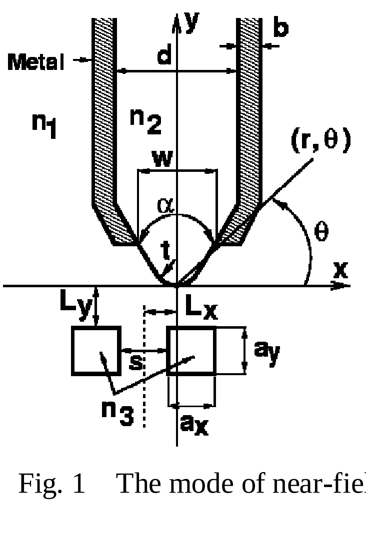
2. Integral Equations

The model of the 2D-SNOM considered in this paper is shown in Fig. 1(a), where the 2D-SNOM is composed of the semi-infinite dielectric-probe and two objects. The dielectric-probe is coated with the metal, which is considered as the perfect electric conductor in this paper, and the waveguide part of the dielectric-probe satisfies the single mode condition. The incident TE-mode or TM-mode comes from the inside of the probe at $y=\infty$ as shown in Fig.1(a).

The following conventional 2-dimensional integral equations are derived from Maxwell's equations:

$$\frac{1}{2}H(\mathbf{x})=\int_{C_t}[G_2(\mathbf{x}|\mathbf{x}')\frac{\partial H(\mathbf{x}')}{\partial n'}-H(\mathbf{x}')\frac{\partial G_2(\mathbf{x}|\mathbf{x}')}{\partial n'}]dl'-\int_{C_{in}}H(\mathbf{x}')\frac{\partial G_2(\mathbf{x}|\mathbf{x}')}{\partial n'}dl', \qquad (1)$$

(a)



Index of refraction

$n_1=1.0$

$n_2=1.5$

$n_3=1.5$

Probe

$d=0.38\lambda$

$t=0.05\lambda$

$b=0.05\lambda$

$\alpha=120$ deg.

Dielectric objects

$a_x=0.16\lambda$

$a_y=0.16\lambda$

$L_y=0.02\lambda$

(b)

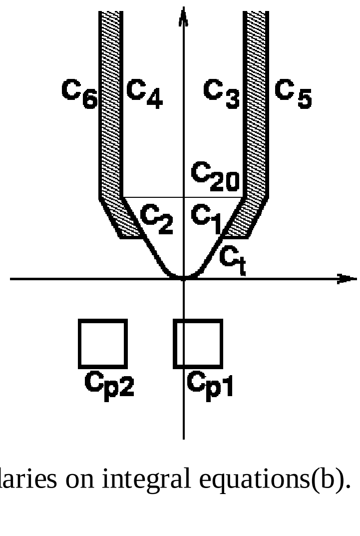


Fig. 1 The mode of near-field optical circuit(a) and the boundaries on integral equations(b).

where $H(\mathbf{x})$ denotes the z-component of the total magnetic field, $G_2(\mathbf{x}|\mathbf{x}')$ represents the two-dimensional Green's function, $\partial/\partial n$ represents the normal derivation of outward direction on the boundary and boundaries C_t and C_{in} that is given by $C_1+C_2+C_3+C_4$ are shown in Fig. 1(b). Since the integral region of Eq. (1) has the semi-infinite length boundary and the total magnetic field on the boundary includes the incident and reflected waves, the infinite terms of basis function must be required when the MoM is applied to Eq. (1).

In order to overcome the difficulty, we consider that the total magnetic field on the boundaries C_3 and C_4, which are parts of boundary C_{in} as shown in Fig. 1(b), is composed of the incident field, reflected field and other field which does not satisfy the mode condition. Namely, the total magnetic field on the boundaries C_3 and C_4 can be expressed as following:

$$H(\mathbf{x}) = H^C(\mathbf{x}) + RH^{+(1)}(\mathbf{x}) + H^{-(1)}(\mathbf{x}), \tag{2}$$

where R indicates the reflection coefficient, $H^{\pm(1)}(\mathbf{x})$ represents the reflected mode(+) and incident mode(-), respectively. The total magnetic field on the boundaries C_t, C_1 and C_2 is denoted by $H^C(\mathbf{x})$ as following:

$$H(\mathbf{x}) = H^C(\mathbf{x}). \tag{3}$$

Substituting Eqs. (2) and (3) into Eq. (1), the following equations can be derived:

$$\frac{1}{2}H^C(\mathbf{x}) = \int_{C_t}[G_2(\mathbf{x}|\mathbf{x}')\frac{\partial H^C(\mathbf{x}')}{\partial n'} - H^C(\mathbf{x}')\frac{\partial G_2(\mathbf{x}|\mathbf{x}')}{\partial n'}]dl'$$

$$-\int_{C_{in}} H^C(\mathbf{x}')\frac{\partial G_2(\mathbf{x}|\mathbf{x}')}{\partial n'}dl' - RU^{+(1)}(\mathbf{x}) - U^{-(1)}(\mathbf{x}), \tag{4}$$

where

$$U^{\pm(1)}(\mathbf{x}) = \int_{C_{20}}[G_2(\mathbf{x}|\mathbf{x}')\frac{\partial H^{\pm(1)}(\mathbf{x}')}{\partial n'} - H^{\pm(1)}(\mathbf{x}')\frac{\partial G_2(\mathbf{x}|\mathbf{x}')}{\partial n'}]dl', \tag{5}$$

and C_{20} denotes a virtual boundary in the probe as shown in Fig. 1(b).

We consider the case that the observation point is far away from the probe-tip, in order to express R in terms of $H^C(\mathbf{x})$ and $\partial H^C(\mathbf{x})/\partial n$. Since, in that case, the Green's function can be asymptotically expressed and it is considered that there is no scattering field in the probe. In the direction of the probe $\theta = \pi/2$, $\partial H^C(\mathbf{x})/\partial\theta$ satisfies the following condition:

$$\frac{\partial H^C(\mathbf{x})}{\partial \theta} = 0 \qquad (r \to \infty) . \tag{6}$$

Then, the unknown coefficient R is expressed by following:

$$R = \{ \int_{C_t} [h_2(\frac{\pi}{2}|\mathbf{x}') \frac{\partial H^C(\mathbf{x}')}{\partial n'} - H^C(\mathbf{x}') \frac{\partial}{\partial n'} h_2(\frac{\pi}{2}|\mathbf{x}')] dl'$$

$$- \int_{C_{in}} H^C(\mathbf{x}') \frac{\partial}{\partial n'} h_2(\frac{\pi}{2}|\mathbf{x}') dl' - v^{-(1)}(\frac{\pi}{2}) \} / v^{+(1)}(\frac{\pi}{2}) , \tag{7}$$

where

$$h_2(\theta|\mathbf{x}') = \frac{\partial}{\partial \theta} g_2(\theta|\mathbf{x}') , \tag{8}$$

$$v^{\pm(1)}(\theta) = \int_{C_{20}} [h_2(\theta|\mathbf{x}') \frac{\partial H^{\pm(1)}(\mathbf{x}')}{\partial n'} - H^{\pm(1)}(\mathbf{x}') \frac{\partial h_2(\theta|\mathbf{x}')}{\partial n'}] dl' . \tag{9}$$

Substituting Eq. (7) into Eq. (4), the new type of integral equation can be derived as:

$$\frac{1}{2} H^C(\mathbf{x}) = \int_{C_t} [P_2(\mathbf{x}|\mathbf{x}') \frac{\partial H^C(\mathbf{x}')}{\partial n'} - H^C(\mathbf{x}') \frac{\partial P_2(\mathbf{x}|\mathbf{x}')}{\partial n'}] dl' - \int_{C_{in}} H^C(\mathbf{x}') \frac{\partial P_2(\mathbf{x}|\mathbf{x}')}{\partial n'} dl' - S_2(\mathbf{x}) , \tag{10}$$

where

$$P_2(\mathbf{x}|\mathbf{x}') = G_2(\mathbf{x}|\mathbf{x}') - h_2(\frac{\pi}{2}|\mathbf{x}') U^{+(1)}(\mathbf{x}) / v^{+(1)}(\frac{\pi}{2}) , \tag{11}$$

$$S_2(\mathbf{x}) = U^{+(1)}(\mathbf{x}) v^{-(1)}(\frac{\pi}{2}) / v^{+(1)}(\frac{\pi}{2}) - U^{-(1)}(\mathbf{x}) . \tag{12}$$

Equation (10) is the proposed integral equation in this paper. As the same procedure for another regions whose refractive indices are given by n_1 and n_3, the integral equations can be derived. They are same forms as that of Eq. (1), where the unknown function $H(\mathbf{x})$ is replaced by $H^C(\mathbf{x})$ which does not satisfy the mode condition. Therefore the infinite length boundaries can be treated as finite length boundary. The proposed integral equations can be numerically solved by the conventional MoM.

3. Computer Simulations

The computer simulation is performed by using the parameters as shown in Fig. 1(a). The three types of the aperture width given by $w = 0.32\lambda$, $w = 0.25\lambda$ and $w = 0.19\lambda$ are considered. It is noted that results of computer simulations are checked by the energy conservation law and they satisfied the law within an accuracy of 1%. The scanning images are shown in Figs. 2(a)-2(d). The abscissa represents x-direction distance between the probe and the center of two objects in Figs. 2(a)-2(d). The ordinate in Figs. 2(a) and 2(b) represents the reflection energy that is normalized by the incident energy. The ordinate in Figs. 2(c) and 2(d) represents the arbitrary unit of the reflection energy.

The reflection energy decreases, when the probe exists above the object for all aperture width as shown in Figs. 2(a) and 2(b). Therefore, the output images can be correctly understood as two objects. It is also found that the reflection energy strongly depends on the width of the aperture as shown in Figs. 2(a) and 2(b). It means that the Signal/Noise ratio can be improved by increasing the width of the aperture. However resolution quality does not so much depend on the width of the aperture as shown in Figs. 2(c) and 2(d).

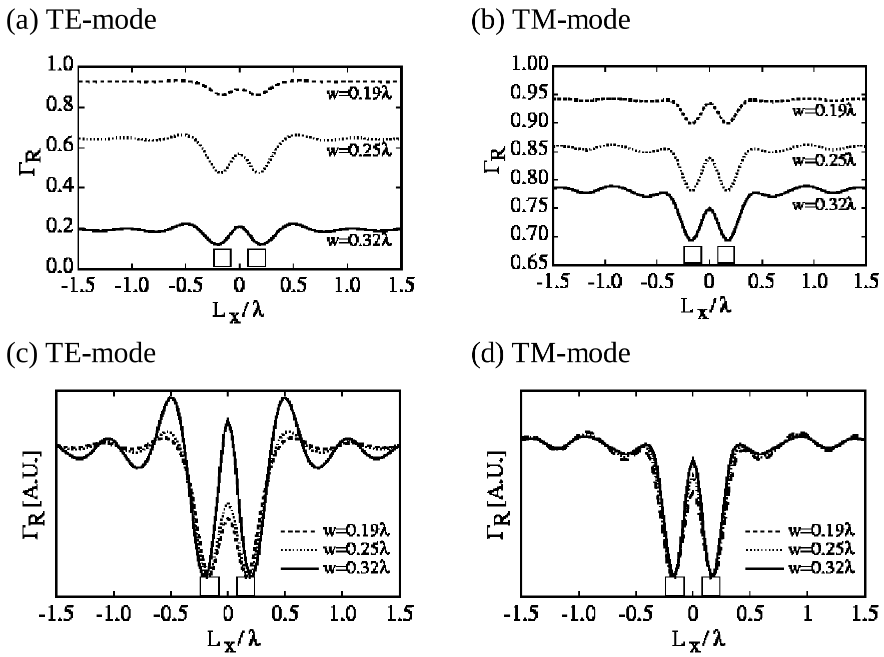


Fig. 2 Output images for the incident TE-mode and TM-mode. The ordinate in (a) and (b) represents the reflection energy normalized by the incident energy. The ordinate in (c) and (d) represents the arbitrary unit.

4. Conclusion

The new type of integral equations for 2D-SNOM using the metal-coated probe with the aperture is derived for the incident TM-mode. The computer simulations were performed for various width of the aperture, in order to investigate the dependence of the resolution quality on the width of the aperture. As the results, the width of the aperture does not almost affect the resolution quality, although it affects the contrast quality.

5. References

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