Simulations of 2D Scanning Near-Field Optical Microscope by Boundary-Element Method based on GMEIE's

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Introduction: Near-field optical (NFO) technology anticipates promising and fantastic applications such as ultra high-resolution optical microscope called scanning near-field optical microscope (SNOM), ultra high-density optical-disc storage system and optical manipulator for a ultra small particle i.e., a single molecule or a single atom [1][2].

In order to analyze NFO circuits in detail we must treat three kinds of optical-fields which are radiation field, near-field i.e., evanescent optical-field, and guided-mode field in the fiber-probe. Therefore, the problems of NFO are very similar to those of integrated optical circuits. In the construction of the simulation-software for NFO circuits, a new method which has high accuracy and wide applicability has been required. Boundary-element method (BEM) based on new integral equations called Guided-Mode Extracted Integral Equation (GMEIE's) for CAD of optical waveguide circuits have been developed [3]-[5]. In this presentation, we apply GMEIE's to simulations of a SNOM and show results by animation which are made on graphic display of SS-20.

Theory: The geometry of the SNOM is shown in Figs. 1(a) and 1(b). We first consider 2D problem for a mathematical simplicity [6]. A SNOM considered in this paper consists of an optical fiber-probe and a small dielectric object placed on the flat substrate. The small object is illuminated by an evanescent optical-field which is created by the total reflection of an incident plane wave which comes from inner side of substrate. Evanescent optical-fields near the object is detected by a tip of the optical fiber-probe. If the fiber-probe is scanned perpendicularly to the axis of fiber-probe in Figs. 1(a) and the transmitted energy in the fiber-probe is measured, we can obtain 1D scanning image of the small dielectric object placed on flat substrate.

It is assumed that the fiber-probe satisfies the single-mode condition and a TE(s-polarization) or a TM(p-polarization) plane wave is incident from the inner side of the substrate to the boundary c_4 as shown in Fig. 1(b). The incident plane wave and reflected plane wave in the substrate are denoted by ψ^i and ψ^r, respectively, and the transmitted evanescent wave above the substrate-surface is denoted by ψ^t. We also denote the guided-mode in the fiber-probe by ψ^g.

A difficulty which arises in this kind of problem as shown in Figs. 1(a) and 1(b) is that we must treat boundaries of infinite-length such as c_1 of the uniform fiber-probe and c_4 of the substrate-surface as shown in Fig. 1(b). The basic idea of GMEIE's is the decomposition of the total fields on these boundaries into field components as follows:

$\psi=\psi^c + T\psi^g$, on the boundary c_1 (1)

$\psi=\psi^c$ on the boundary c_2+c_3 (2)

$\psi=\psi^c + \psi^t$ on the boundary of substrate c_4 (3)

$\psi=\psi^c + \psi^i+ \psi^r$, under the boundary of substrate c_4 (4)

Boundary integral equations for unknowns ψ^c and $\partial\psi^c/\partial n$ can be derived by using procedures which are shown in references [3] -[5] and resultant GMEIE's which are similar to conventional boundary integral equations can be derived as follows [7]-[9]:

$$\psi^c(x)/2=\int_{C_1+C_2+C_3+C_4}[P_1(x|x')\partial\psi^c/\partial n'-\psi^c(x')\partial P_1(x|x')/\partial n']dl'+\psi^t \quad (5)$$

$$\psi^c(x)/2=\int_{C_1+C_2}[P_2(x|x')\partial\psi^c/\partial n'-\psi^c(x')\partial P_2(x|x')/\partial n']dl' \quad (6)$$

$$\psi^c(x)/2=\int_{C_3}[G_3(x|x')\partial\psi^c/\partial n'-\psi^c(x')\partial G_3(x|x')/\partial n']dl' \quad (7)$$

$$\psi^c(x)/2=\int_{C_4}[G_4(x|x')\partial\psi^c/\partial n'-\psi^c(x')\partial G_4(x|x')/\partial n']dl' \quad (8)$$

where

$$P_j(x|x')=G_j(x|x')-g_2(\pi/2|x')U_j(x)/u_2(\pi/2) \; (j=1,2) \quad (9)$$

$$G_j(x|x')=-j/4H_0^{(2)}(k_0n_j|x-x'|) \quad (j=1,2,3,4) \quad (10)$$

$$g_2(\theta|x')=\exp(jn_2k_0x'\cos\theta+jn_2k_0y'\sin\theta) \quad (11)$$

and

$$U_j(x)=\int_{C_{1j}}[G_j(x|x')\partial\psi^g/\partial n'- \psi^g(x')\partial G_j/\partial n']dl' \quad (j=1,2) \quad (12)$$

$$u_2(\theta)=\int_{C_{12}}[g_2(\theta|x')\partial\psi^g/\partial n'- \psi^g\partial_2(\theta|x')/\partial n']dl' \quad (13)$$

Simultaneous boundary integral equations (5)-(8) can be solved numerically by the conventional BEM or moment-method (MoM). From definitions in equations (1)-(4), fields ψ^c and $\partial\psi^c/\partial n$ on the boundaries $c_i(i=1-4)$ of SNOM as shown in Figs. 1(a) and 1(b) will become zero sufficiently far away from the origin of x-y coordinates in Fig. 1(a). In other words, we can treat the problem of this SNOM like the scattering problem of isolated objects of finite size by using GMEIE's. If once ψ^c and $\partial\psi^c/\partial n$ on all boundaries can be obtained, the amplitude of the guided-mode in the optical-fiber probe T can be obtained as

$$T=\int_{C_1+C_2}[g_2(\pi/2|x')\partial\psi^c/\partial n'-\psi^c g_2(\pi/2|x')/\partial n']dl'/u_2(\pi/2) \quad (14)$$

It must be noticed that the validity of numerical results obtained by the above-mentioned method can be checked by optical theorem which can be newly derived as:

$$1/(8\pi)\int_{0}^{2\pi}|B(\theta)|^{2}d\theta+\beta\,|T|^{2}\int_{-\infty}^{\infty}|\psi g|^{2}dx=Im[N\,R^{*}(\theta_i)B(3\pi/2-\theta_i)] \quad (15)$$

where $B(\theta)$ represents scattering coefficient, $R^*(\theta_i)$ represents a complex conjugate of total reflection coefficient for incident angle θ_i as shown in Fig. 1(a) and β represents a propagation constant of the guided-mode in the fiber-probe. Constant N is unity for TE-mode and $1/n_4^2$ for TM-mode, where n_4 is index of refraction of substrate. Optical-fields in various regions can be calculated from conventional integral presentations.

Numerical Examples: We denote various parameters of the microscope as shown in Figs. 1(a) and (b) as follows:

Distance between probe axis and object in x direction:	l_x
Distance between probe axis and object in y direction:	l_y
Tip angle of fiber-probe	: φ
Radius of curvature of fiber-probe tip	: R
Radius of circular object on substrate	: r
Width of fiber-probe	: a
Index of refraction in surrounding space	: n_1
Index of refraction of optical fiber-probe	: n_2
Index of refraction of the object	: n_3
Index of refraction of the substrate	: n_4
Incident angle of the plane wave	: θ_i

We made animations which present distributions of optical-fields near the probe-tip and the object, and dependence of transmission coefficient T on l_x and l_y i.e., 1D image of the SNOM on the system SS-20 as shown in Fig.2. It is useful to understand physical processes which occur in the SNOM as shown in Figs. 1(a) and 1(b) by using this animation.

CONCLUSION: New boundary integral equations called GMEIE's have been applied to simulations of a 2D SNOM. Since new boundary integral equations can be solved rigorously by the conventional BEM or MoM, it is suitable for the basic theory of simulation-software for various NFO problems.

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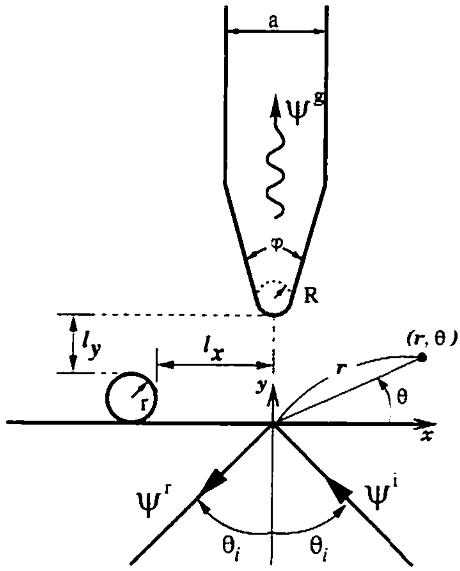

Fig. 1(a) Geometry of scanning near-field microscope (SNOM).

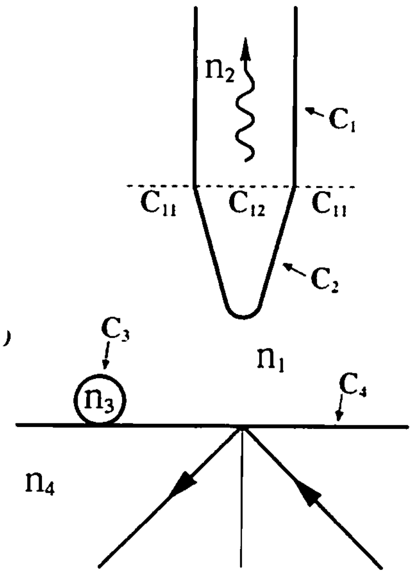

Fig. 1(b) Indices of refraction and boundaries of uniform fiber-probe, probe-tip, object and substrate surface.

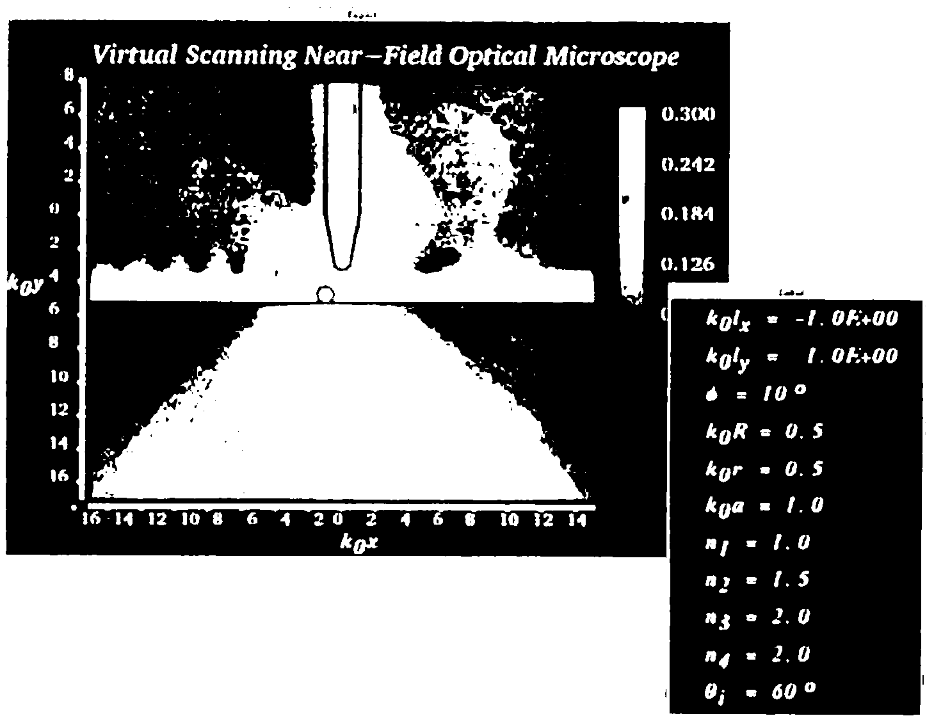

Fig.2 Distribution of calculated optical-field near probe-tip and object. Incident and reflected waves are omitted in the substrate.