Near-field optics has been studied intensively over the past decade as a new discipline that is promising for overcoming the traditional diffraction limit of far-field optics. Experimentally, resolution far beyond the diffraction limit has been achieved in many applications by use of near-field scanning optical microscopes (NSOM’s). However, in detailed analysis of the experimental data one always encounters two kinds of difficulty. One kind is technical, owing to parameters of the measurement, such as the aperture shape and the quality of the metal coating surrounding the NSOM probes, which are currently difficult to control. The other is a theoretical and fundamental problem that is still not well understood: How is information on the subwavelength scale encoded in the near field, and how is that information modified during a measurement when those near-fields are converted into the propagating fields that are eventually detected?

To address the latter issue more clearly we examine the experimentally obtained radiation fields emitted from a near-field probe, using a multipole expansion method. This method provides a systematic way to analyze the radiation from a localized source. The optical function of a NSOM probe in illumination mode can be described by an expansion of multipoles in the following way:

$$\text{NSOM probe} = \sum_{l,m} \left[ a_M(l,m) \text{MMP}(l,m) + a_E(l,m) \text{EMP}(l,m) \right],$$  

where MMP($l$, $m$) and EMP($l$, $m$) are magnetic and electric multipoles of orders $l$ and $m$, respectively. Since NSOM probes have an aperture smaller than the wavelength, the coefficients associated with high-order multipoles are negligible in the far field, so the radiation comes mainly from low-order nonvanishing terms in the expansion. In the near-field regime, however, high-order multipoles play a relatively more important role. When a probe approaches a sample, the near fields are deformed to satisfy the local electromagnetic boundary conditions, and this results in changes in the coefficients in the multipole expansion. In this case, only low-order multipoles contribute to the detectable far field, since the probe–sample combination can still be assumed to be smaller than the wavelength. Therefore, one can specify information from an illumination-mode NSOM as the changes in the coefficients of low-order multipoles to reflect local optical information from the sample surface. From this viewpoint, a good model for explaining near-field interactions focuses on the behavior of low-order multipole sources modified by the additional boundary conditions imposed by the sample surface.

To date, simple dipole schemes have been used to describe NSOM images. The use of simple schemes has been motivated by results from the classical model of a small hole in a perfectly conducting infinite plane in the limit of $ka << 1$, where $a$ is the aperture radius and $k$ is the wave vector, $2\pi / \lambda$. The far-field radiation from the aperture is identical to that of a radiating magnetic dipole located at the center of the aperture for a normally incident plane wave. However, a real NSOM probe has an aperture that is not on an infinitely conducting plane but is at the end of a tapered optical fiber coated with a metal that is not perfectly conducting. The discrepancy between the classical model and a real probe was reported by Obermuller and Karrai. They measured the angular distribution of radiation diffracted by NSOM probes and reported an empirical relation between the aperture sizes and the FWHM of the distribution. They found that the addition of an electric dipole along the incident electric field could fit the polar–angular distribution along the magnetic field direction. However, this combination did not satisfy the distribution in the normal direction. Moreover, no combination of just two dipoles could explain the radiation from NSOM probes. That this

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Received September 21, 1999
is so suggests that higher-order multipoles are induced in the probe even when its aperture is much smaller than the wavelength.

In this Letter we report on polarization-resolved measurements of the far-field radiation distribution from NSOM probes and analyze the results in terms of low-order multipoles. In principle, for a complete specification of the coefficients in the expansion it is necessary to know the radial components of the electric and the magnetic fields in a source-free region; this is practically impossible in far-field measurements, in which the fields are transverse. However, for a localized source whose dimensions are small compared with a wavelength, only a few dominant low-order multipoles are represented in the angular distribution of radiated power. Magnetic and electric multipole fields of order \(l, m\) that are appropriate for radiation from a localized source are defined by

\[
\begin{align*}
E^M_{lm} &= h_i^{(1)}(kr)X_{lm}(\theta, \phi), \\
B^M_{lm} &= -\frac{i}{k} \nabla \times E^M_{lm}, \\
E^E_{lm} &= h_i^{(1)}(kr)X_{lm}(\theta, \phi), \\
B^E_{lm} &= \frac{i}{k} \nabla \times B^E_{lm},
\end{align*}
\]

where \(X_{lm}\) and \(h_i^{(1)}\) are the normalized vector spherical harmonics and the Hankel functions for outgoing waves, respectively. In the radiation zone \((kr > 1)\), the fields become transverse, so they can be analyzed as components along the unit vectors, \(\theta\) and \(\phi\). We define the two components as

\[
\begin{align*}
\theta_{lm}(\theta, \phi) &= \theta \cdot X_{lm}(\theta, \phi) = -\frac{m}{\sin \theta} \frac{Y_{lm}(\theta, \phi)}{\sqrt{l(l+1)}}, \\
\phi_{lm}(\theta, \phi) &= \phi \cdot X_{lm}(\theta, \phi) = -i \frac{\partial}{\partial \theta} \frac{Y_{lm}(\theta, \phi)}{\sqrt{l(l+1)}}.
\end{align*}
\]

Then, for a combination of multipoles, the angular distributions of the two polarization components are

\[
\begin{align*}
I_\theta(\theta, \phi) &= \left| \sum_{l,m} (-i)^{l+1} [a_M(l,m)\theta_{lm}(\theta, \phi) + a_E(l,m)\phi_{lm}(\theta, \phi)] \right|^2, \\
I_\phi(\theta, \phi) &= \left| \sum_{l,m} (-i)^{l+1} [a_M(l,m)\theta_{lm}(\theta, \phi) - a_E(l,m)\phi_{lm}(\theta, \phi)] \right|^2.
\end{align*}
\]

Figure 1 shows the experimental setup for obtaining the polarization-resolved angular intensity distribution of the radiation from NSOM probes. We use commercial probes that have a 100-nm aperture at the end of a tapered optical fiber and launch 810-nm-wavelength light from a high-power semiconductor laser into the fiber. The emitted angular distribution is measured with a solid-angle scanner that consists of a detector capable of scanning the surface of a sphere centered at the source point. Light is collected by a fiber bundle with a 1-mm-diameter aperture and detected with a photomultiplier. A polarizer in front of the fiber bundle entrance rotates to determine the polarization state at each solid angle. The data are collected over a polar angle \(\theta\) stretching from 0° to 150° from the normal and over the full 360° in \(\phi\). The polarization state of the radiation is controlled by a variable wave plate placed at the input to the fiber. A full description of the experimental apparatus can be found in Ref. 8.

For a cylindrically symmetric NSOM probe, it is preferable to take circular polarization rather than linear polarization as a basis, since the multipoles are eigenstates of angular momentum. For a left-handed (right-handed) circularly polarized state, only \(m = 1(-1)\) terms are required for angular momentum conservation to be satisfied. The two-dimensional intensity distribution and the local polarization state across the pattern for circular polarization are depicted in Fig. 2. The extinction ratio curve in Fig. 2(b) shows that circular polarization in the forward direction gradually changes into an elliptical state and eventually reaches a linear state as the polar angle increases. Moreover, the polarization-direction curve shows that the elliptical and the linear states are directed radially everywhere in the pattern shown in Fig. 2(a), which is along the \(\phi\) direction on the surface of the sphere. This result implies that the \(\theta\) component decreases faster than the \(\phi\) component as the polar angle increases and that the two components are 90° out of phase for all directions. This phase constraint simplifies the relation among multipoles existing at the aperture of the probe. If we notice that \(\theta_{lm}\) and \(\phi_{lm}\) are orthonormal, it is straightforward to verify that \(a_M(l, \pm 1), a_E(l, \pm 1), a_M(l + 1, \pm 1), a_E(l, \pm 1), a_M(l + 1, \pm 1)\) should be 90° out of phase.

With this phase information for the coefficients, we fit the intensity distributions for two polarization components along \(\theta\) and \(\phi\) simultaneously. These two components can be measured in a linearly polarized case, in which they manifest themselves individually.

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**Fig. 1.** Schematic representation of the experimental setup: PMT, photomultiplier; PD, photodiode; LD, laser diode.
Fig. 2. Radiation field from the near-field optical probe for input light that is circularly polarized: (a) two-dimensional intensity distribution. The data over the curved surface of sphere $r_0$ are represented on a flat surface $x$, $y$ by a mapping, $\theta = \pi(x^2 + y^2)^{1/2}$ and $\phi = \text{Arg}(x + yi)$. The scan range is $0^\circ \leq \theta \leq 120^\circ$. The circle with the arrow indicates the polarization. (b) Extinction ratio and local polarization direction along the line shown in (a).

Fig. 3. (a), (b) Radiation fields from the near-field optical probe for input light that is linearly polarized. The double arrows indicate the polarization direction. The scan range is $0^\circ \leq \theta \leq 150^\circ$. The line scan is (c) along and (d) normal to the polarization direction as shown in (b). The solid curves are the fitted curves with parameters taken from Table 1. Each square denotes a data point.

**Table 1. Normalized Coefficients of Magnetic and Electric Multipoles ($l$, $m$) for Left-Handed Circularly Polarized Input**

<table>
<thead>
<tr>
<th>Type</th>
<th>Dipole $(1, 1)$</th>
<th>Quadrupole $(2, 1)$</th>
<th>Octupole $(3, 1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic</td>
<td>1</td>
<td>$-0.04i$</td>
<td>$-0.1$</td>
</tr>
<tr>
<td>Electric</td>
<td>$-0.59i$</td>
<td>0.06</td>
<td>$0.06i$</td>
</tr>
</tbody>
</table>

along and normal to the polarization direction. In Fig. 3 the measured $\theta$ and $\phi$ components and the best fit with dipole, quadrupole, and octupole terms are presented. The coefficients are listed in Table 1. The multipole decomposition shows that the dipole components are dominant. The strong magnetic dipole radiation reflects the fact that the induced surface currents near the aperture are the main radiation source. The considerable electric radiation is due to the surface-charge density, which stems from the finite conductivity of the metal coating or the taper structure. As a result, the magnetic and the electric dipoles should be considered together if we are to aim for a realistic dipole model for near-field optical probes. The coefficients of the quadrupoles and the octupoles are found to be relatively small. The intensity contributions of the higher-order poles themselves are 2 orders smaller than those of the dipoles. However, the interference terms between the dipoles and the high-order poles alter the radiation significantly, since they are only 1 order smaller than those of the dipoles.

The multipole fit is nearly perfect except for the high polar angle region in which the detector reaches a geometric limit owing to the taper angle. Since the taper angle is not constant near the aperture, we cannot clearly identify the limit beyond which the radiation from the aperture stops propagating freely and instead begins to interact with the metal coating on the taper. Actually, complicated fringes in the intensity or the depolarization effects that are thought to result from the metal coating are often observed in other probes. Therefore, data at high polar angles near $150^\circ$ may contain new effects.

In summary, we find that the radiation emanating from a subwavelength aperture in a near-field optical probe can be represented by low-order terms in a multipole expansion based on vector spherical waves. More generally, multipole analysis provides a useful way to express near-field optical interactions in an illumination-mode NSOM.

We thank H. Ando of NTT Basic Research Laboratories for his encouragement throughout this work.

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