The localized and enhanced optical near-field on the asymmetric metal-coated dielectric probe

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1. Introduction

As recent trends of integrated optical circuits shows the features of small size, high speed, and flexible structures are expected by many researchers as well as optical devices manufacturers. Many functional devices utilizing surface plasmon polaritons (SPPs) have been proposed and are expected to play an important role in future of nanometric integrated optical circuit [1-4]. There is difficulty in the coupling of incident light into metallic nanostructures since conventional optics cannot focus a laser beam into a region that is much smaller than about half the wavelength of the light due to the diffraction limit of light. Metal-coated dielectric conical probe supporting SPPs can perform above-mentioned function by significantly enhanced and localized near-fields at the tip [1, 2]. These focusing techniques are often called SPP superfocusing or nanofocusing so far. However the symmetric conical probe can be used only for radially polarized (RP) incident field [5-7]. In the practical applications, the linearly polarized (LP) mode in the thin optical fibre will be used [8]. Unfortunately, the symmetric conical probe is not valid for incident LP beam. In order to use the incident LP beam in the metal-coated dielectric conical probe, we propose the structure of asymmetric shape for SPP nanofocusing.

In the present study, the volume integral equations (VIE) method is used to investigate nanofocusing of SPPs by conical metal-coated dielectric probe with asymmetric shape. Based on the VIE method we show the different behaviour of nanofocusing by symmetric and asymmetric probes. Results provide insight in the mechanism of guiding and nanofocusing in complicated SPP tapering geometries and show how such nanofocusing can be achieved using a conical metal-coated dielectric probe.

2. Configuration of the problem

A schematic diagram of the asymmetric metal-coated conical dielectric probe is shown in Fig.1. The conical dielectric probe with a relative permittivity \( \varepsilon_1 \) is fabricated in the \((x, y, z)\) coordinate system. The conical probe has a base radius \( R \) and a height \( h \). The side of conical dielectric probe is coated with the metal with a relative permittivity \( \varepsilon_2 \) and thickness \( d \). The surrounding free space has a permittivity \( \varepsilon_0 \). This conical probe shown in Fig. 1 is not rotationally symmetric about z-axis. In order define the degree of asymmetric structure, we define the distance between tip and z-axis \( l \) shown in Fig. 1. The case of \( l=0 \) correspond to the symmetric probe.

The radial and z components of electric field of the RP incident Gaussian beam at \( z=0 \) can be written as [9, 10]:

\[
E_r(r, 0) = 2A(r/w)exp[-(r/w)^2] \\
E_z(r, 0) = -j4A[1-(r/w)^2]/(k_0w)exp[-(r/w)^2]
\] (1)
For the LP incident Gaussian beam, the incident electric field at \( z=0 \) can be written as [8]

\[
\begin{align*}
E_x(r, 0) &= A \exp[-(r/w)^2] \\
E_y(r, 0) &= 0 \\
E_z(r, 0) &= jA(2x/w^2) \exp[-(r/w)^2]
\end{align*}
\]

In Eqs. 1 and 2, \( k_0 \) is the wavenumber in free space, \( w \) is the spot size of the beam and \( r = (x^2 + y^2)^{1/2} \). The beam amplitude is given by \( A = 1 \) and RL and LP beams of Eqs. 1 and 2 have same incident energies at \( z = 0 \). The RP and LP optical fields of the SPPs are excited along the asymmetric surface of the probe. The optical fields of the SPPs are nanofocused by the decreasing cross section of the probe in the propagation direction.

We solve the scattering problem shown in Fig. 1 by the VIE method [1, 3]. We first discretize the whole structure shown in Fig. 1 using tiny cubes; i.e., we consider that the conical structures are composed of cubes with \( \delta \times \delta \times \delta \) dimensions shown in the inset of Fig. 1. Then we discretize the VIE by the moment-method and finally solve the resultant system of linear equations numerically by general minimum residual method with fast Fourier transformation. In this paper, the wavelength (\( \lambda \)) is 633 nm and \( \delta \) is given by \( k_0 \delta = 0.05 \) (\( \delta = 5 \) nm). The metal coating is gold (Au) whose permittivity is given by \( \varepsilon_2 / \varepsilon_0 = -13.8-j1.08 \) and relativity of the dielectric is given by \( \varepsilon_2 / \varepsilon_0 = 2.25 \). The beam spot size of is given by \( w = \lambda \) at \( z = 0 \) and the thickness is given by \( k_0 d = 0.27 \) (\( d = 27.4 \) nm). Base radius of the asymmetric conical structure show in Fig. 1 is given by \( k_0 R = 7.07 \) (\( R = 712 \) nm). Probes have a height given by \( k_0 h = 16.4 \) (\( h = 1652 \) nm).

### 3. Optical intensity distributions

We discretize the whole structure using cubes arranged in 328 layers parallel to the x-y plane (see the inset of Fig. 1). Here we present numerical results how a RP or LP beam is focused into the asymmetrical conical metal-coated dielectric probe and show how a highly confined electric field is generated. Figures 2(a) and (b) show the distributions of the optical intensity in the x-z plane for the symmetric probe and asymmetric probe, respectively, for LP incident beam. In Fig. 2(a), we can see that the optical intensity is not focused at the tip for the case of symmetric probe. However, the optical intensity is focused at the tip for the case of the asymmetric probe shown in Fig. 2(b). Figures 2(c) and (d) show the results for symmetric and asymmetric probes, respectively, for the incident RP beam. In Figs. 2(c) and (d), for the incident RP beams, we can see that the enhanced and localized optical intensity at the tip can be realized for symmetric and asymmetric probes. The optical intensity is decreased significantly with increase of the degree of asymmetry, i.e., distance \( l \).
Figure 2: Optical intensity distributions on the x-z plane for symmetric probe (l=0 nm) and asymmetric probe (l=300 nm). The optical intensities of $|E(x, 0, z)|^2$ for incident LP beam are shown in (a) and (b). The optical intensities for incident RP beam are shown in (c) and (d). The metal coating is Au ($\varepsilon = -13.8 - 1.08$). The dielectric is glass ($\varepsilon_z/\varepsilon_0 = 2.25$).

4. Dependence of maximum optical intensity on the distance $l$

The dependence of the maximum enhanced optical intensity at the tip on the distance $l$ is shown in Fig. 3. In this study, the distance $l$ is varied from 0 nm to 600 nm. The ordinates mean results of the incident RP beam (left) and the incident LP beam (right). Figure 3 reveals that the maximum optical intensity strongly depends on the distance $l$. It is found that symmetric probe (l=0 nm) is the most suitable for incident RP beam and the maximum optical intensity decreases with the increase of distance $l$ (see Fig. 3). For incident LP beam, we found the existence of the optimum distance $l$ where the maximum optical intensity can be obtained at the tip. In Fig. 3, the maximum optical intensity has the largest value at distance $l$ is equal to about 300 nm.

Table 1: The maximum optical intensity $|E|^2$ in the region of 349.5 nm < $l$ < 598.4 nm

<table>
<thead>
<tr>
<th>Distance $l$ (nm)</th>
<th>349.5</th>
<th>409.9</th>
<th>471.5</th>
<th>534.2</th>
<th>598.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>E</td>
<td>^2$ (for RP beam)</td>
<td>5732</td>
<td>3062</td>
<td>1409</td>
</tr>
<tr>
<td>$</td>
<td>E</td>
<td>^2$ (for LP beam)</td>
<td>5033</td>
<td>4382</td>
<td>3707</td>
</tr>
</tbody>
</table>

The results in Fig.3 show that the maximum optical intensities at the tip for incident RP beam are larger than those for incident LP beam in the regions of distance $l$ that is smaller than about 400 nm. However, when distance $l$ is greater than about 400 nm, the maximum optical intensity for incident LP beam is larger than that for incident RP beam (See Table 1).
5. Conclusion

In this paper, we investigated the basic characteristics of the maximum optical intensity at the tip created by nanofocusing in the SPP metal-coated conical dielectric probe with asymmetric shape by the volume integral equation method. We consider the cases of radially polarized and linearly polarized incident Gaussian beams and found that the asymmetric SPP conical probe is valid for incident linearly polarized beam. Since the degree of the asymmetric shape of the probe affects significantly the maximum enhanced optical intensity at the tip for incident RP and LP beams, the findings of this study demonstrate that asymmetric conical probes must be carefully designed and fabricated.

References