Field enhancement analysis of an apertureless near field scanning optical microscope probe with finite element method

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Plasmonic field enhancement in a fully coated dielectric near field scanning optical microscope (NSOM) probe under radial polarization illumination is analyzed using an axially symmetric three-dimensional (3D) finite element method (FEM) model. The enhancement factor strongly depends on the illumination spot size, taper angle of the probe, and the metal film thickness. The tolerance of the alignment angle is investigated. Probe designs with different metal coatings and their enhancement performance are studied as well. The nanometric spot size at the tip apex and high field enhancement of the apertureless NSOM probe have important potential application in semiconductor metrology.

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Near field scanning optical microscopy (NSOM) provides subwavelength resolving power based on the detection of evanescent wave in the near field[1,2]. There are two types of NSOMs, apertured NSOM and apertureless NSOM. Apertureless NSOM can overcome the disadvantage of low throughput in apertured NSOM. In the apertureless NSOM, usually an extremely sharp dielectric, semiconductor, or metallic tip is used as a Rayleigh scattering probe. If a metallic probe is used, the local excitation of surface plasmon at the probe tip provides a significant local field enhancement. However, sophisticated illumination geometry is required to excite the localized mode on the tip and large far field background noise contaminates the near field signal.

Recently, there is an increasing research interest in the local field distribution at the vicinity of a nanometric apertureless NSOM tip[3−5]. In order to eliminate the background noise, apertureless NSOM probes using fully metal-coated conical dielectric structures under radially polarized internal light illumination were proposed and studied. It is shown that this configuration could provide optimal plasmonic focusing, hence the optimal filed enhancement[6,7]. In this paper, we use a three-dimensional (3D) finite element method (FEM) model to numerically study the dependence of the enhancement factor on various design parameters of the probe. From our simulations, we found that the enhancement factor is closely related to probe design parameters, such as the illumination spot size, taper angle of the probe, and the metal film thickness. The dependence of enhancement factor on misalignment of illumination angle is investigated as well. Finally, probe designs with different metal coatings materials (gold and aluminum) and their enhancement performance are explored.

The geometry of proposed probe is shown in Fig. 1. A sharp conical fiber tip with half cone angle of 16.4° and radius of curvature of 20 nm at the tip end is used. The entire tip is coated with 50-nm silver film which has a radius of curvature of 5 nm at the end. The dielectric constants of the fiber core and silver thin film at the excitation wavelength of 632.8 nm are chosen to be 2.2 and $-15.8779 - 1.0765i$, respectively. Radially polarized beam is injected into the fiber on the top. Radially polarized beam has radial symmetry both in amplitude and polarization. It remains continuous research interests and has important application in ultrasmall spot focusing and high resolution metrology[8]. When radially polarized beam is coupled into the probe, the entire beam is TM polarized with respect to the whole structure. Surface plasmon will be generated at the silver/glass interface and constructively interfere at the tip end due to the rotational symmetry of both the probe tip and polarization state of illumination, providing an enormously enhanced nanometric spot.

An axial symmetry finite element model was applied to investigate the field enhancement in the vicinity of the tip end. In the model, a continuous physical problem is converted into a discretized finite element problem described by Maxwell partial differential equations with appropriate boundary conditions. The method requires the division of the geometry of the problem into sub regions or cells. A commercial FEM software called COMSOL was used in the simulation. The 3D axial symmetry model in COMSOL is perfect for our problem

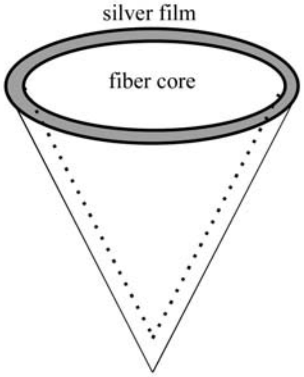

Fig. 1. Diagram of proposed apertureless NSOM probe tip.

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due to the rotational symmetry of both the geometry structure and the polarization state of illumination. For axial symmetric geometry, there are variations in the radial (r) and vertical (z) direction only and no variations in the azimuthal (θ) direction. One can then solve a quasi two-dimensional (2D) problem in the r-z plane instead of the full 3D model, saving considerable memory and computational time. To model and simulate the field distribution problem, in the first step, we choose axial symmetry model, draw the geometry, and specify the dielectric constant of each subdomain. Then, different boundary conditions are defined at each interface. Glass/silver and silver/air interfaces are automatically defined by the continuity of the tangential electromagnetic wave. Electric field and absorption boundary conditions are applied to the bottom of the probe and outmost environment respectively. We set the input radially polarized beam to be

$$\vec{E}(r) = r \cdot \exp[-(r/w)^2]\overrightarrow{e_r}, \tag{1}$$

where r is the radial coordinate and w is the beam waist of the incident light, which is equal to 0.4 μm. Besides, the maximum allowable mesh sizes at all the subdomains, boundaries, and points are specified to ensure the accuracy of the calculation.

Examples of the simulated 2D and 3D plots for electrical energy density distributions, spot size measurement, and dependence of field enhancement on taper angle of probe tip and illumination spot size have been reported in Ref. [7]. In this letter, further investigations are made to systematically analyze the effects of designing parameters on the probe performance. To explore the optimal condition for the electric field enhancement, we study the influences of the metal thin film thickness on the field enhancement. Figure 2 shows the relationship between electric field enhancement factor and the silver thin film thickness. We find that the optimal thickness is about 55 nm for the tip with a taper angle of 16.4°. While from Fig. 3, we find that the spot size (hence the spatial resolution) is almost unchanged, which remains about 6 nm. Essentially, the spot is determined by the radius of the tip.

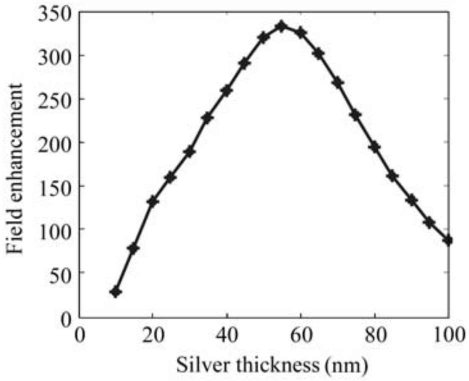

Fig. 2. Dependence of electric field enhancement on silver film thickness.

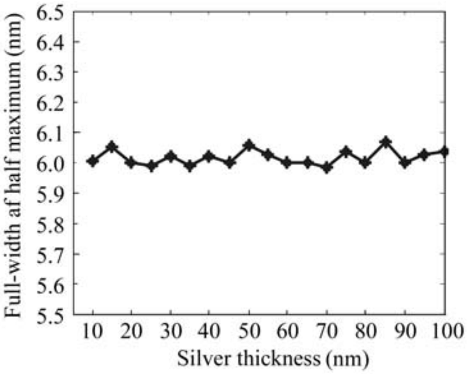

Fig. 3. Dependence of spot size at tip end on silver film thickness.

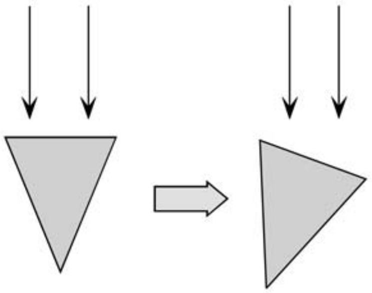

Fig. 4. Misalignment of probe tip and illumination.

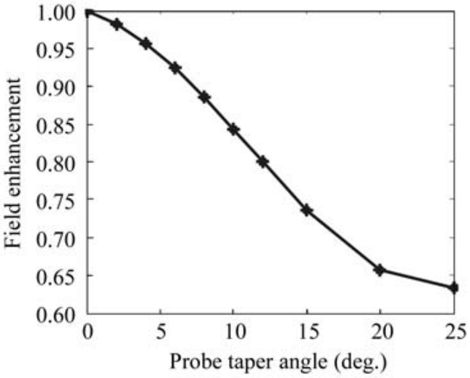

Fig. 5. Normalized field enhancement factor with respected to misalignment of illumination angle.

We also investigate the tolerance of the illumination alignment angle, because some probes can be operated under tapping mode for probe-sample distance regulation (illustrated in Fig. 4). For this study, a full 3D COMSOL model has to be used due to the break of symmetry by the deflection angle. When the radially polarized beam is focused into the cone tip with a small tilt angle, which may happen because of the vibration of the tip, the enhancement factor decreases as expected. However, it remains a relatively high value for fairly large deflection angles. Figure 5 shows the normalized field enhancement factors at different tilt angles compared with those of normal incidence.

Moreover, probe designs with different metal coatings (gold and aluminum) and their enhancement performance are studied as well. Figures 6(a) and (b) illustrate the electric field enhancement factor dependent on taper angle of probe for gold and aluminum, respectively. We can see that the performance of gold gives better performance at the excitation wavelength, which is due to its smaller absorption coefficient. Similarly, owing to a

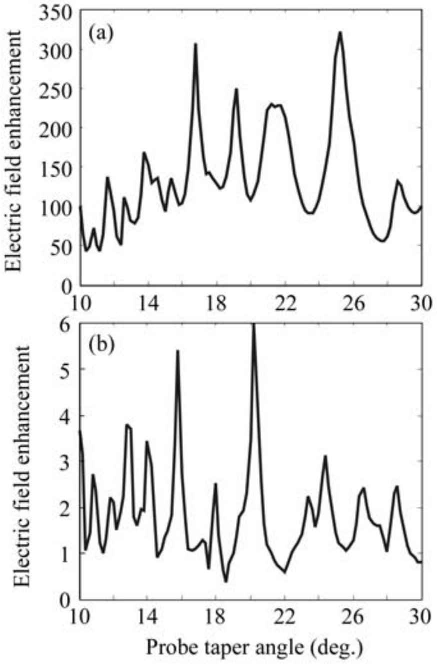

Fig. 6. Electric field enhancement factor with respect to half taper angle of probe for (a) 50-nm gold coating, and (b) 50-nm aluminum coating.

big absorption coefficient, the field enhancement of aluminum is much lower with 50-nm film thickness.

In conclusion, this study provide the necessary knowledge for manufacturing and optimizing the probe for apertureless NSOM that may have many applications including field-enhanced Raman spectroscopy for nanomaterials characterization and nano-devices metrology.

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