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Surface plasmon excitation and localization by asymmetric metal-coated dielectric probe

By
Ngo Thi Thu

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHYLLOSOPHY IN ENGINEERING

AT
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Abstract

This thesis presents the study on the asymmetric metal-coated dielectric conical probe in the practical applications on the optical fiber.

For the purpose of developing the probe using surface plasmon polariton (SPP) nanofocusing that is valid for incident linearly polarized (LP) wave, the asymmetric metal-coated dielectric conical probe is investigated numerically by the volume integral equation. It is found that it possible to perform SPP nanofocusing using this probe for incident LP Gaussian beam in addition to incident radially polarized (RP) beam. The basic characteristics of the strongly localized and enhanced optical near-fields on the tip of the probe and optical intensities inside the probe are investigated. For the incident LP beams, it is found that the optimum structure of the partially metal-coated dielectric probe exists. For the case of incident RP beam, partial metal-coating of the probe degrades the characteristic of nanofocusing, i.e., fully metal-coated conventional probe is the optimum shape for incident RP beam.

In order to perform the SPP nanofocusing of LP waves, a variety of structures have been studied and investigated [1-8]. The authors have also proposed the idea using metal-coated dielectric probe of tilted conical shape and have shown that this probe is valid for both incident LP and RP waves [9-10]. The idea of SPP nanofocusing by using LP waves is based on the destruction of interference cancellation of SPPs at the tip by the asymmetric structure of the probe.

In the other way, in order to achieve the SPP nanofocusing for incident LP beam by the dielectric conical probe, another asymmetric structure of the probe, i.e., the partially metal-coated dielectric probe is proposed. We can consider that partially metal-coating also destruct the interference cancellation among SPPs on the tip.
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Chapter 1

1. Introduction

Physics would be dull and life most unfulfilling if all physical phenomena around us were linear. Fortunately, we are living in a nonlinear world. While linearization beautifies physics, nonlinearity provides excitement in physics. My study has been researching in surface nonlinear optics that how to create the strongly nanolocalized optical fields.

1.1 Overview of surface plasmon polariton

A surface plasmon polariton (SPP) is an electromagnetic (EM) excitation existing on the surface of a good metal. It is an intrinsically two-dimensional excitation whose electromagnetic field decays exponentially with distance from the surface. In its simplest form a surface plasmon polariton (SPP) is an electromagnetic excitation that propagates in a wave like fashion along the planar interface between a metal and a dielectric medium, often vacuum, and whose amplitude decays exponentially with increasing distance into each medium from the interface. The SPP cannot be excited directly by photon, because the wave-vector of the SPP is larger than that of the photon. The properties of SPP mode can be deduced from a solution of Maxwell’s equations at the boundary of the metal and dielectric media.

The existence of surface plasmon EM waves was predicted by Sommerfeld as early as 1909. They appear in a variety of circumstances. The ground wave propagation on
earth is just one example. Here we are concerned with surface EM waves on condensed matter.

Recent theoretical and experimental studies of nanometric integrated optical circuits that employ surface plasmon polaritons (SPPs) have shown that functional devices utilizing SPPs can be expected to play an important role in future of nanometric integrated optical circuits. For example, optical waveguide circuits based on SPPs can be miniaturized much further than conventional diffraction-limited optical waveguide circuits [1-8], opening up the possibility of developing nanometric integrated optical circuits.

Nanofabricated systems that exploit SPPs demonstrate potential for designing and controlling the propagation of light in matter. In particular, SPPs can be used to channel light efficiently into nanometer scale volumes, leading to direct modification of resonate frequency dispersion properties (substantially shrinking the wavelength of light and the speed of light pulses for example), as well as field enhancements suitable for enabling strong interactions with nonlinear materials. The resulting enhanced sensitivity of light to external parameters (for example, an applied electric field or the dielectric constant of an adsorbed molecular layer) shows great promise for applications in sensing and switching.

Current research is focused on the design, fabrication, and experimental characterization of novel components for measurement and communications based on nanoscale plasmonic effects. These devices include ultra-compact plasmonic interferometers for applications such as biosensing, optical positioning and optical switching, as well as the individual building blocks (plasmon source, waveguide and detector) needed to integrate a high-bandwidth, infrared-frequency plasmonic
communications link on a silicon chip.

In addition to building functional devices based on SPPs, it appears feasible to exploit the dispersion characteristics of SPPs traveling in confined metallo-dielectric spaces to create photonic materials with artificially tailored bulk optical characteristics, otherwise known as metamaterials.

The excitation of SPPs is frequently used in an experimental technique known as surface plasmon resonance (SPR). In SPR, the maximum excitation of surface plasmons are detected by monitoring the reflected power from a prism coupler as a function of incident angle or wavelength. This technique can be used to observe nanometer changes in thickness, density fluctuations, or molecular absorption.

Surface plasmon-based circuits, including both SPPs and localized plasmon resonances, have been proposed as a means of overcoming the size limitations of photonic circuits for use in high performance data processing nano devices.

The ability to dynamically control the plasmonic properties of materials in these nano-devices is key to their development. A new approach that uses plasmon-plasmon interactions has been demonstrated recently. Here the bulk plasmon resonance is induced or suppressed to manipulate the propagation of light. This approach has been shown to have a high potential for nanoscale light manipulation and the development of a fully CMOS-compatible electro-optical plasmonic modulator.

CMOS compatible electro-optic plasmonic modulators will be key components in chip-scale photonic circuits.

In surface second harmonic generation, the second harmonic signal is proportional to the square of the electric field. The electric field is stronger at the interface because of the surface plasmon resulting in a non-linear optical effect. This larger signal is often
exploited to produce a stronger second harmonic signal.

The wavelength and intensity of the plasmon-related absorption and emission peaks are affected by molecular adsorption that can be used in molecular sensors. For example, a fully operational prototype device detecting casein in milk has been fabricated. The device is based on monitoring changes in plasmon-related absorption of light by a gold layer.

1.2 Exciting SPP mode into nanometric optical waveguide circuits

In order to excite the surface plasmon polaritons into nanometric optical waveguide circuits, the optical waves generated by the laser source must be focused into the space whose size is much smaller than the wavelength, i.e., the nanosize space. The metal-coated dielectric probe can create the significantly localized and enhanced near-fields in the nanosized region near the tip. This focusing technique is often called SPP nanofocusing or superfocusing so far [6-16] and it has been applied to the optical probe of scanning near-field optical microscope (SNOM). The metal-coated dielectric probe of conical shape is one of fundamental devices in nanophotonics utilizing SPPs [9-16].

Recently plasmonic lasers that directly generate nanoscale light, essentially using electronic transitions as a focusing mechanism while also coherently sustaining it by amplification has been widely interested and will be a promising techniques of making nanosized optical electromagnetic fields [17]. However, SPP nanofocusing by the metal-dielectric probe is also useful due to low-cost and easy fabrication in the future.
1.3 Motivation for this work

Recent theoretical and experimental studies of nanometric integrated optical circuits that employ surface plasmon polaritons (SPPs) have shown that functional devices utilizing SPPs can be expected to play an important role in future of nanometric integrated optical circuits. For example, optical waveguide circuits based on SPPs can be miniaturized much further than conventional diffraction-limited optical waveguide circuits [1-20], opening up the possibility of developing nanometric integrated optical circuits.

In order to excite the surface plasmon polaritons into nanometric optical waveguide circuits, the optical waves generated by the laser source must be focused into the space whose size is much smaller than the wavelength, i.e., the nanosize space. The metal-coated dielectric probe can create the significantly localized and enhanced near-fields in the nanosized region near the tip. This focusing technique is often called SPP nanofocusing or superfocusing so far [9-16] and it has been applied to the optical probe of scanning near-field optical microscope (SNOM). The metal-coated dielectric probe of conical shape is one of fundamental devices in nanophotonics utilizing SPPs [9-16].

Recently plasmonic lasers that directly generate nanoscale light, essentially using electronic transitions as a focusing mechanism while also coherently sustaining it by amplification has been widely interested and will be a promising techniques of making nanosized optical electromagnetic fields [17]. However, SPP nanofocusing by the metal-dielectric probe is also useful due to low-cost and easy fabrication in the future.

The symmetric metal-coated dielectric conical probe is valid only for the incident radially polarized (RP) beam and is not valid for the incident linearly polarized (LP)
beam. It is cumbersome to change the incident LP light to the RP light in the practical optical applications. Thereupon, the nanofocusing which is valid for the incident LP light is preferable in the practical applications because the polarization of dominant mode in the optical fiber is LP mode (HE11-mode), i.e., linearly polarized wave.

In order to perform the SPP nanofocusing of LP waves, a variety of structures have been studied and investigated [9-16]. The idea of SPP nanofocusing by using LP waves is based on the destruction of interference cancellation of SPPs at the tip by the asymmetric structure of the probe.

1.4 Outline of this dissertation

This dissertation is composed of five chapters. This chapter presents the overview of surface plasmon polariton, how to exciting surface plasmon polaritons into nanometric optical waveguide circuits, motivation for this work as well as an overview of the components of this dissertation.

Chapter 2 presents the theory for calculation of propagation constant and the field distribution of a waveguide problem. We discretize the volume integral equation (VIE) by the method of moments using roof-top functions as basis and testing functions in each cubes and finally solve the resultant system of linear equations numerically by the iteration method called generalized minimum residual (GMRES) with Fast Fourier Transformation (FFT).

Chapter 3, by the volume integral equation method, the metal-coated dielectric probes of tilted conical shape were investigated for nanofocusing of surface plasmon polaritons for incident Linearly polarized Gaussian beam then compare to results of incident Radially polarized Gaussian beam.
Chapter 4, for the purpose of developing the probe using surface plasmon polariton nanofocusing that is valid for incident linearly polarized (LP) wave, the partially metal-coated dielectric conical probe is investigated. Here, we investigate the localized and enhances intensity on the tip for LP wave and compare to results for Radially polarized wave. Moreover, we investigate the effect of the curvature at the tip of the probe to the maximum enhanced optical intensity at the tip for both incident RP and LP beams.
Chapter 2

2. Calculating method

We first divide three-dimensional models of the probe into tiny cubes having dimensions of \( \delta \times \delta \times \delta \) to solve the scattering problem. Then, we discretize the volume integral equation (VIE) by the method of moments using roof-top functions as basis and testing functions in each cube and finally solve the resultant system of linear equations numerically by the iteration method called generalized minimum residual (GMRES) with Fast Fourier Transformation (FFT).

2.1 Maxwell equations

The behaviour of electromagnetic fields in the presence of material media is governed by Maxwell’s equations of macroscopic electrodynamics:

\[
\nabla \times E = -j \omega \mu_0 H \quad \text{(Faraday’s induction law)}
\]

\[
\nabla \times H = j \omega \varepsilon_i E \quad \text{(generalized Ampère’s circuitial law)}
\]

where

- \( E \) = electric field strength (V/m)
- \( H \) = magnetic field strength (A/m)
- \( \varepsilon_i \) is relative permittivity of the material.
- \( \mu_0 \) is the magnetic permeability of a vacuum (\( \mu_0 = 4\pi \times 10^{-7} \text{H/m}^2 \))
Chapter 3 Metal-coated dielectric probe of tilted conical shape

2.1.1 Maxwell–Faraday equation

\[ \nabla \times E = -j\omega \mu_o H \]

\[
\begin{vmatrix}
i_x & i_y & i_z \\
\frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\
E_x & E_y & E_z
\end{vmatrix} = -j\omega \mu_o H
\]

\[
i_x \left( \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \right) + i_y \left( \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} \right) + i_z \left( \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \right) = -j\omega \mu_o H \quad (1)
\]

2.1.2 Ampère's circuital law

\[ \nabla \times H = j\omega \varepsilon_i E \]

\[
\begin{vmatrix}
i_x & i_y & i_z \\
\frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\
H_x & H_y & H_z
\end{vmatrix} = j\omega \varepsilon_i E
\]

\[
i_x \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \right) + i_y \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \right) + i_z \left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right) = j\omega \varepsilon_i E \quad (2)
\]

where

- \( \mu_o \) = permeability in free space
- \( \varepsilon_0 \) = permitivity in free space
- \( \varepsilon \) = relative permitivity of the material

\[ \mu_o = 4\pi \times 10^{-7} \left( \frac{\text{Henry}}{\text{meter}} \right), \quad \varepsilon_i = \varepsilon \varepsilon_0, \varepsilon_0 = 8.85 \times 10^{-12} \text{F/m} \]
2.2 Surface electromagnetic waves at a dielectric–metal interface

EM radiation is divided from TM and TE modes. TM mode is including $E_x, E_z, H_y$ and TE mode is including $H_x, H_z, E_y$.

In the Figure 2.1, a p-polarized (transverse magnetic or TM) wave in this structure propagates in the $x$-direction.

The electromagnetic field of a surface plasmon polariton at a dielectric–metal interface is obtained from the solution of Maxwell’s equations in each medium, and the associated boundary conditions. The latter express the continuity of the tangential components of the electric and magnetic fields across the interface, and the vanishing of these fields infinitely far from the interface. To introduce the main parameters characterizing surface plasmon polaritons, let us consider a system consisting of a dielectric material, characterized by an isotropic, real, positive dielectric constant $\varepsilon_1$, in the half-space $z > 0$, and a metal, characterized by an isotropic, frequency-dependent, complex dielectric function $\varepsilon_2 = \alpha(\omega) + j\beta(\omega)$ in the half-space $z < 0$ (Fig. 1).

We first consider a p-polarized (transverse magnetic or TM) wave in this structure that

![Figure 2.1: Surface plasmon polariton at a dielectric–metal interface.](image)
propagates in the $x$-direction. (Due to the optical isotropy of the two media there is no loss of generality in choosing this direction of propagation.) In a wave of this polarization the magnetic vector is perpendicular to the plane of incidence, the plane defined by the direction of propagation and the normal to the surface. The solutions of Maxwell’s equations that are wavelike in the $x$-direction and whose amplitudes decay exponentially with increasing distance into each medium from the interface $z=0$ can be written as

From Eq. 1:
$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -j\omega \mu_0 H_y \quad (3)$$

From Eq. 2:
$$\begin{cases} \frac{\partial H_y}{\partial z} = j\omega \varepsilon_1 E_x \\ \frac{\partial H_y}{\partial x} = j\omega \varepsilon_1 E_z \end{cases} \quad (4)$$

From Eq. 4,5 into Eq. 3:
$$\frac{\partial}{\partial z} \left( -\frac{1}{j\omega \varepsilon_i} \frac{\partial H_y}{\partial z} \right) - \frac{\partial}{\partial x} \left( \frac{1}{j\omega \varepsilon_i} \frac{\partial H_y}{\partial x} \right) = -j\omega \mu_0 H_y$$

$$-\frac{1}{j\omega \varepsilon_i} \frac{\partial^2 H_y}{\partial z^2} - \frac{1}{j\omega \varepsilon_i} \frac{\partial^2 H_y}{\partial x^2} = -j\omega \mu_0 H_y$$

$$\frac{1}{j\omega \varepsilon_i} \left( \frac{\partial^2 H_y}{\partial x^2} + \frac{\partial^2 H_y}{\partial z^2} \right) = j\omega \mu_0 H_y$$

$$\omega^2 \mu_0 \varepsilon_i H_y + \frac{\partial^2 H_y}{\partial x^2} + \frac{\partial^2 H_y}{\partial z^2} = 0 \quad (6)$$

The slab is infinitely extended in $y$-$z$ plane. Since we are interested in obtaining the normal modes of the slab waveguide, we assume that the $z$-dependence of the mode
fields is given by the function $e^{-j\beta z}$, so that function $e^{j(\omega t - \beta z)}$ describes a wave traveling in positive $z$-direction with phase velocity

$$\theta = \omega / \beta. \text{ So } \frac{\partial H_y}{\partial z} = -j\beta H_y \ (7)$$

Eq. 7 $\rightarrow$ Eq. 6:

$$\omega^2 \mu_o \varepsilon_i H_y + (-j \beta)^2 H_y + \frac{\partial^2 H_y}{\partial x^2} = 0$$

$$\omega^2 \mu_o \varepsilon_i H_y - \beta^2 H_y + \frac{\partial^2 H_y}{\partial x^2} = 0$$

$$\frac{\partial^2 H_y}{\partial x^2} + (\varepsilon k_0^2 - \beta^2)H_y = 0 \ (8)$$

$$k_0^2 = \omega^2 \mu_o \varepsilon_o = \left(\frac{2\pi}{\lambda}\right)^2$$

$$k^2 = \varepsilon k_0^2$$

From Eq. 8:

If $(\varepsilon k_0^2 - \beta^2) = h_1^2 > 0: \ H_y = Acosh_1x + Bsinh_1x \ (9)$

If $(\varepsilon k_0^2 - \beta^2) = -h_2^2 < 0: \ H_y = Ce^{h_2x} \ (10)$
2.3 Surface electromagnetic waves at dielectric slab waveguide

Figure 2.2 shows a p-polarized wave propagates in the $x$-direction of dielectric slab waveguide.

From Eq. 8, 9 and 10:

$$\begin{cases} 
\frac{\partial^2 H_y}{\partial x^2} + h_1^2 H_y = 0 & x < 0 \\
\frac{\partial^2 H_y}{\partial x^2} - h_2^2 H_y = 0 & 0 < x < d \\
\frac{\partial^2 H_y}{\partial x^2} + h_3^2 H_y = 0 & d < x 
\end{cases}$$  \hspace{1cm} (11)

$$\begin{cases} 
H_y = A \cosh x + B \sinh x & x < 0 \\
H_y = Ce^{h_2 x} & 0 < x < d \\
H_y = Ce^{h_3 d}(A \cosh (x - d) + B \sinh (x - d)) & d < x 
\end{cases} \hspace{1cm} (12)$$

where

$$\begin{cases} 
(\varepsilon_1 k_0^2 - \beta^2) = h_1^2 & (13) \\
(\varepsilon_2 k_0^2 - \beta^2) = -h_2^2 & (14) \\
(\varepsilon_3 k_0^2 - \beta^2) = h_3^2 & (15) 
\end{cases}$$
From Eq. 4, 5, 7:

\[
E_x = \frac{-1}{j\omega \varepsilon_i} \frac{\partial H_y}{\partial z} = \frac{-1}{j\omega \varepsilon_i} (-j\beta H_y) = \frac{\beta}{\omega \varepsilon_i} H_y
\]  

(16)

\[
E_z = \frac{1}{j\omega \varepsilon_i} \frac{\partial H_y}{\partial x}
\]  

(17)

\[
= \frac{1}{j\omega \varepsilon_i} \left\{ \begin{array}{ll}
-h_1 \text{Asinh}_1 x + h_1 \text{Bcosh}_1 x \\
h_2 \text{Ce}^{h_2x}
\end{array} \right. \\
\text{Ce}^{h_2d}[(h_2B - h_3A)\text{sinh}_3(x - d) + (h_2A + h_3B)\text{cosh}_3(x - d)]
\]  

(18)

Boundary conditions

\[
\begin{align*}
\{ n \times (E_1 - E_2) &= 0 \\
(n \times (H_1 - H_2)) &\text{ is surface current density}\, J_s = 0 \}
\end{align*}
\]

At \( x = 0 \)

\[
H_y = A\text{cosh}_1 x + B\text{sinh}_1 x = \text{Ce}^{h_2x}
\]

\[
A = C
\]

\[
E_x = \frac{1}{j\omega \varepsilon_1} (-h_1 \text{Asinh}_1 x + h_1 \text{Bcosh}_1 x) = \frac{1}{j\omega \varepsilon_2} h_2 \text{Ce}^{h_2x}
\]

\[
h_1 B \varepsilon_2 = h_2 C \varepsilon_1
\]

\[
\frac{B}{C} = \frac{h_2 \varepsilon_1}{h_1 \varepsilon_2}
\]

And \( x = d \)

\[
H_y = \text{Ce}^{h_2x} = \text{Ce}^{h_2d} (A\text{cosh}_3(x - d) + B\text{sinh}_3(x - d))
\]

\[
A = 1
\]

\[
E_x = \frac{1}{j\omega \varepsilon_2} h_2 \text{Ce}^{h_2x}
\]

\[
= \frac{1}{j\omega \varepsilon_3} \text{Ce}^{h_2d}[(h_2B - h_3A)\text{sinh}_3(x - d) + (h_2A + h_3B)\text{cosh}_3(x - d)]
\]
2.4 Surface polariton scattering

Surface polariton scattering by surface features is a basis for SPP applications. It plays a crucial role in determining optical properties of rough and nanostructured metal films, and is a key for understanding all SPP related processes. The SPP interaction with a surface defect can be described by three processes, namely, scattering of SPP into SPP propagating in another direction (or SPP reflection), propagation of SPP through the defect region in the same direction as the incoming SPP (SPP transmission), and scattering of SPP into light. In the past, using conventional far-field measurements, it has only been possible to study the latter process. All investigations of surface polaritons have been based on such far-field observations of the intensity and angular distribution of the light scattered due to the interaction of SPP with surface features [1]. It was possible to modify the surface structure in one or another (generally unknown) way and to follow the changes in the scattered light behavior without knowledge of the SPP scattering processes on a surface. With the development of SNOM these in-plane scattering processes can be directly studied by measuring the electromagnetic field distribution related to the surface polaritons in the near-field region over a surface. The interplay between in-plane and out-of-plane scattering processes determines the

\[
\begin{align*}
\frac{h_2}{\varepsilon_2} &= \frac{(h_2 A + h_3 B)}{\varepsilon_3} \\
B &= \frac{h_2 (\varepsilon_3 - \varepsilon_2)}{h_3 \varepsilon_3} \\
\frac{h_1}{h_3} &= \frac{\varepsilon_1 \varepsilon_3}{\varepsilon_2 (\varepsilon_3 - \varepsilon_2)}
\end{align*}
\]
character of the electromagnetic field distribution over a surface and, therefore, surface optical properties and the field enhancement. The scattering processes depend on the size, geometrical shape, and the dielectric constant of the surface features. The surface polariton scattering is a complex phenomenon which in most cases (except for very simple geometries) requires tedious numerical modeling. Similar to all wave scattering processes, the SPP scattering depends on the relation between a defect size and the SPP wavelength. Nevertheless, since a surface polariton is an intrinsically two-dimensional excitation, two characteristic defect sizes should be considered: one characterizing the lateral (in-plane) size of the defect and another characterizing the defect height (out-of-plane size). To understand SPP scattering processes, these characteristic sizes of scatterers should be related to respective in-plane and out-of-plane characteristics of the surface polariton wave: SPP wavelength and SPP field extension from the surface, respectively. In addition, the gradient of the topography variations should be taken into account. Naturally for a slowly varying topography the SPP scattering will be less important. Thus, the efficiency of the in-plane and out-of-plane SPP scattering by surface features depends in a nontrivial way on the lateral size, height (or depth) of a defect through their relations to the SPP wavelength, and on the SPP field extension length above (or below) a surface.

2.5 Volume Integral Equation Method

We first divide three dimensional models of the probe into tiny cubes having dimensions of $\delta \times \delta \times \delta$ to solve the scattering problem. Then, we discretize the volume integral equation (VIE) by the method of moments using roof-top functions as basis and testing functions in each cubes and finally solve the resultant system of linear
Chapter 3 Metal-coated dielectric probe of tilted conical shape

equations numerically by the iteration method called generalized minimum residual (GMRES) with Fast Fourier Transformation (FFT). We consider two cases of incident beam in this paper, i.e., the LP and RP Gaussian beams. Both beams, whose axis coincides with z-axis, are assumed to be incident along the z-axis from negative z direction. For the LP Gaussian beam which is polarized in the x-direction, the x, y, z components of electric field at z = 0 can be written as [19-23];

\[ E_x(x, y, 0) = A \exp[-(r/w)^2] \]
\[ E_y(x, y, 0) = 0 \]
\[ E_z(x, y, 0) = j A [2x/(k_0 w^2)] \exp[-(r/w)^2] \]  

(19)

The radial and z components of electric field of the incident RP Gaussian beam at z = 0 can be written as [9-13];

\[ E_r(r, 0) = 2A (r/w) \exp[-(r/w)^2] \]
\[ E_z(r, 0) = - \frac{j A}{k_0 w} \left[ \frac{r}{w} \right]^2 \exp[-(r/w)^2] \]  

(20)

In Eqs.1 and 2, \( k_0 \) is the wavenumber in the free space, \( w \) is the spot size of the beam and \( r = (x^2 + y^2)^{1/2} \). The beam amplitude is given by \( A=1 \) in Eqs. 1 and 2 and both LP and RP beams have the same incident energies at z = 0. The LP and RP optical fields excite SPPs along the partially metal-coated surface of the probe. The optical fields of the SPPs are focused by decreasing the cross section of the probe along the propagation direction and make the strongly localized and enhanced fields on the tip. Through my research, the wavelength \( \lambda \) is 633 nm and the sized of discretized cube \( \delta \) is given by \( k_0 \delta = 0.05 \) (\( \delta = 5 \text{nm} \)). The beam spot size of is given by \( w=\lambda \) at z=0.
Figure 2.3: The arrangement of cubes in the top 14 layers of probe. The inset shows the tiny cube with \( \delta \times \delta \times \delta \) dimensions.

Consider the scattering of an inhomogeneous dielectric object embedded within a finite volume \( V \). The complex permittivity of the object is

\[
\varepsilon_r(r) = \varepsilon_r \varepsilon_0 - \frac{j \sigma(r)}{\omega}
\]  

(21)

where \( \varepsilon_r \) and \( \sigma(r) \) denote the relative permittivity and the electric conductivity, respectively. Suppose the object is illuminated by an incident electric field \( E^i \). The volume integral equation for this problem can then be described by

\[
\frac{D(r)}{\varepsilon_r} - (k_0^2 + \nabla \cdot )A(r) = E^i(r)
\]

(22)

with \( k_0 = \omega \sqrt{\mu_0 \varepsilon_0} \) and

\[
A(r) = \frac{1}{\varepsilon_0} \int_V G(r - r') \chi(r') D(r') dr'
\]

(23)

where \( \chi(r) = \frac{\varepsilon(r) - \varepsilon_0}{\varepsilon(r)} \) and \( G(r - r') = \frac{\exp(-jk_0|r - r'|)}{4\pi|r - r'|} \).

Using the weak form of electric flux density, the electric-contrast vector potential and the incident electric field in (23) and expanding and testing the corresponding terms with 3D vector volumetric rooftop functions, a matrix equation can be obtained as follows:

\[
Ax = b
\]
The matrix equation can be solved efficiently by Generalized Minimum Residual Method with Fast Fourier Transformation.
Chapter 3

3. Superfocusing of SPPs by metal-coated dielectric probe of tilted conical shape

By the volume integral equation method, the metal-coated dielectric probes of tilted conical shape were investigated for nanofocusing of surface plasmon polaritons (SPPs). We consider the cases of incident radially polarized and linearly polarized Gaussian beams and found that the tilted SPP conical probe is valid for both incident linearly and radially polarized beams. Compare to the other asymmetric structures reported so far which are valid for the incident linearly polarized waves, the structure proposed in this paper is not only simple but also straightforward to obtain the nanofocused localized and enhanced optical field on the tip for incident linearly polarized beam.

3.1 Introduction

The recent explosive progress in nano-optics has been based on the nanoscale local fields that are greatly enhanced due to resonant properties of metal nanosystems. Surface plasmon polaritons (SPPs) in nanostructured systems enable one to observe propagation, interference, and imaging on the nanoscale [1]. The strongly nanolocalized optical fields induce many enhanced nonlinear-optical phenomena and have various prospective applications. Metal-coated dielectric conical probe supporting SPPs can perform above-mentioned function by creating enhanced local fields at the tip [2], [3]. This focusing technique is often called SPP superfocusing or nanofocusing so far [1], [3-9]. The metal-coated dielectric probes of conical shape will be one of fundamental devices in nanophotonics utilizing SPPs [3-18].
Chapter 3 Metal-coated dielectric probe of tilted conical shape

There are some problems in making the nanofocused optical fields at the tip of the probe. For example, the conical probe whose shape is rotationally symmetric around center axis is only valid for incident radially polarized (RP) field [3], [11], [18]. Therefore the structure which is suitable for the incident linearly polarized (LP) field such as HE11 mode in the optical fiber is required. In order to solve the above problem, in the previous works, a variety of asymmetric structures have been studied and investigated, including asymmetrically corrugated fully metal-coated probe [13], rectangular slits defects in the metal coating layer of the near-field scanning optical microscopy (NSOM) probe [14], offset apertured NSOM probe [15], and uncorrugated probes with many grooves [17]. All topographies appeared in those paper are based on symmetric conical structure. The asymmetric probe is created by adding or cutting something on the original symmetric probe. Besides, the results shown in those studies have not included the concrete values of the optical intensities. In this paper, we introduce a new, simple and straightforward shape of asymmetric metal-coated dielectric conical probe, i.e., the tilted conical shape. Furthermore, we evaluate the basic characteristic of the probe by using concrete values of the optical intensities. The proposed tilted metal-coated dielectric conical probe supporting SPPs can make the significantly enhanced local fields at the tip for the case of incident LP beam.

The characteristics of the enhanced local fields that are nanofocused near the probe tip have been studied by many authors using the numerical techniques including finite-difference time-domain (FDTD) method [11], [14], [15], the finite element method (FEM) [12], the finite integration technique (FIT) [8] and the volume integral equation (VIE) method [3-6].

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

In this paper, we analyze the basic characteristics i.e., optical field at the tip, of the metal-coated dielectric probe of tilted conical shape. We first show the dependences of the maximum enhanced local optical intensities at the tip on the degree of asymmetry of the tilted probe for both incident RP and LP beams for various coating metals. Then, we vary the polarized angle of the LP beam and show the dependence of the maximum optical intensity at the tip on the polarized angle.

3.2 Geometry of the problem

We consider the metal-coated dielectric probe of tilted conical shape shown in Fig. 3.1. The dielectric conical probe has a base radius $R$ and was made of a dielectric with a relative permittivity $\varepsilon_1/\varepsilon_0$ fabricated in the $(x, y, z)$ coordinate system where $\varepsilon_0$ is permittivity of free space. The side of conical dielectric probe is coated with the thin metal with a relative permittivity $\varepsilon_2/\varepsilon_0$ and thickness $d$. The surrounding is the free space. The conical probe has a height $h$. It is apparent that the conical probe shown in Fig. 3.1 is not rotationally symmetric about z-axis. In order to define the degree of asymmetry of tilted conical shape, we employ the distance $l$ between tip and the z-axis shown in Fig. 3.1. The case of $l=0$ corresponds to the symmetric probe and the cases of non-zero values of $l$ correspond to the tilted probes.
Figure 3.1: Geometry of the tilted metal-coated conical dielectric probe. The conical dielectric
structure has a base radius $R$ and a height $h$. The metal coating has a thickness $d$. The tip of the probe is located at $(l, 0, h)$ in the $(x, y, z)$ coordinate system. Permittivities of the surrounding free space, the coating metal, and the dielectric of the conical structure are denoted by $\varepsilon_0$, $\varepsilon_1$, and $\varepsilon_2$, respectively. The shape of the tilted conical structure is characterized by distance $l$ between the $z$-axis and the tip. Both radially and linearly polarized Gaussian beams are normally incident to the $x$-$y$ plane from negative $z$-direction. The axis of Gaussian beam coincides with the $z$-axis. Radially and linearly polarized beams propagate along the $z$ direction and polarization of the linearly polarized beam makes an angle of $\beta$ with the $x$-axis. Figure (b) show the discretized structure of only 28 layers near the tip of the probe. The whole structure is composed of 328 layers. The inset shows the tiny cube with $\delta \times \delta \times \delta$ dimensions. The asymmetric probe is displayed on (b) $z$-$y$ plane, (c) $z$-$x$ plane and (d) $x$-$y$ plane.

Despite the rapid progress of numerical methods and computer hardware, full 3D simulations of NSOM tips that are simultaneously large compared with the wavelength and exhibit very small features are extremely time consuming and usually do not provide sufficient accuracy. Therefore, we divide 3D models of the probe into tiny cubes having dimensions of $\delta \times \delta \times \delta$ in the VIE method to solve the scattering problem shown in Fig. 3.1 [1, 3]. We first discretize the whole structure shown in Fig. 3.1 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. 3.1. 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 $k_0d=0.27$ ($d=27.4$ nm). Base radius of the asymmetric conical structure show in Fig.1 is given by $k_0R = 7.07$ ($R=712$ nm). Probes have a height given by $k_0h = 16.4$ ($h=1652$ nm). As the simulations are extremely computationally intensive because of the different scales of the distance $l$ and the metal coating, the whole probe is examined. We analyze the effect of a change in these parameters with optical intensity distribution.

3.3 Nanofocused optical intensities

We discretize the whole structure using cubes arranged in 328 layers parallel to the $x$-$y$ plane (28 layers near the tip are shown in Fig. 1(b)). Here we present numerical results how a RP or LP beam is focused by the metal-coated dielectric conical probe of tilted shape and show how a highly confined electric field at the tip is generated.

Figures 3.2(a) and (b) show the distributions of the optical intensities by logarithmic scale on the $x$-$z$ plane ($\log(|E(x,0,z)|^2)$) and figures 3.2(c) and (d) on the $y$-$z$ plane ($\log(|E(0,y,z)|^2)$) for the symmetric probe for incident LP and RP beams, respectively. In Fig. 3.2(a) and (c), we can see that the optical intensity is not focused at the tip of the symmetric probe for the case of incident LP beam in both $x$-$z$ and $y$-$z$ planes. However, the optical intensity is focused at the tip of this probe for the case of the incident RP beam in Fig. 3.2(b) and (d). These results can be explained by Fig. 3.3 that shows the illustrations of the electric field vector on the $x$-$z$ plane of symmetric probe.
Chapter 3 Metal-coated dielectric probe of tilted conical shape

(a) $\log(|E(x, 0, z)|^2)$

(b) $\log(|E(x, 0, z)|^2)$

(c) $\log(|E(0, y, z)|^2)$

(d) $\log(|E(0, y, z)|^2)$
Chapter 3 Metal-coated dielectric probe of tilted conical shape

Figure 3.2: Optical intensity distributions on the x-z plane and y-z plane for symmetric probe ($l=0$ nm) and tilted probe ($l=300$ nm) are shown in the logarithmic scale. The optical intensities of $\log(|E(x, 0, z)|^2)$ and $\log(|E(0, y, z)|^2)$ for symmetric probe for incident LP and RP beams are shown in (a), (b), (c) and (d), respectively. The optical intensities of $\log(|E(l, y, z)|^2)$ and $\log(|E(l, y, z)|^2)$ for tilted probe for incident LP and RP beams are...
shown in (e), (f), (g) and (h), respectively. The coating metal is Au ($\varepsilon_2/\varepsilon_0 = -13.8 - j1.08$). The dielectric is glass ($\varepsilon_1/\varepsilon_0 = 2.25$). Other parameters keep constant ($d \approx 27.4$nm, $R = 712$nm, $h = 1652$nm).

In Fig. 3.3(a), we can see that, for the case of the incident LP beam, the $x$-component of the electric vectors of the excited SPP has same direction on the right and left surfaces of the probe. Contrary, their $z$-component has opposite direction on the right and left surfaces. The main component of the nanofocused electric field on the tip has the $z$ direction. The electric field vectors which propagate along the right and left surface have opposite direction on the tip in Fig. 3.3(a). Therefore the electric field vector is cancelled at the tip of the probe. For the incident RP beam, the $z$-component of the electric vectors of the excited SPP have same direction on the right and left surfaces, as shown in Fig. 3.3(b). Therefore the electric field is not cancelled and moreover the optical intensity is focused at the tip of probe.

Figures 3.2(e) and (f) show the distributions of the optical intensities by logarithmic scale on the $x$-$z$ plane ($\log(|E(x,0,z)|^2)$) and figures 3.2(g) and (h) $y$-$z$ plane ($\log(|E(l,y,z)|^2)$) for the tilted probe ($l = 300$nm) for incident LP and RP beams, respectively. With the tilted conical shape, we can see that the optical intensity for incident LP beam is focused and enhanced at the tip in Fig. 3.2(e). Moreover, for incident RP beam, the enhanced and localized optical intensity at the tip can be also realized for tilted probe (in Fig. 3.2(f)). It means that the tilted conical shape is valid for both incident LP and RP beams.
3.4 Dependence of maximum optical intensity on the distance \( l \)

The dependences of the maximum enhanced optical intensities at the tip on the degree of asymmetry i.e., distance \( l \) are shown in this part.

The nanofocused maximum intensity exists at a point just above the tip in the free space in Fig. 3.4. Since the probe is composed by the cubes with size \( \delta = 5\text{nm} \) in this paper, this point is located at 2.5nm just above the surface of the tip cube. We use the value of
the intensity at this point as the maximum of optical intensity in this paper.

We investigated structures with four various coating metals that are Au, Cu, Al and Ni. Figure 3.5 reveals that the maximum optical intensity strongly depends on the distance $l$ for all coating metals for radially polarized waves. For all cases of asymmetric structure, the distance $l$ is varied from 0nm to 600nm under the condition that the other parameters of the shape are not changed. The results of the incident RP beam are shown in Fig. 3.5(a) for the cases of coating metals are Au and Cu, and in (b) for the cases of Al and Ni. 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 $l$ (shown in Fig. 3.5(a) and (b)).

For the metal Au, the maximum optical intensity is largest in all coating metals. Interestingly, Cu gives a large enhanced optical intensity of $\sim 2.0 \times 10^4$ shown in Fig. 3.5(a) and rather large enhanced optical intensities can be also generated even by metals having large dissipations ($\sim 1.0 \times 10^3$ for Ni and $\sim 8.2 \times 10^2$ for Al) shown in Fig. 3.5(b). For incident RP beam, the maximum enhanced optical intensities in Fig. 3.5(a) for Au, Cu (small values of dissipation of metal) are much larger than those in Fig. 3.5(b) for Al, Ni (large values of dissipation of metal).
Figure 3.5: The maximum of optical intensity at the tip $|E|^2$ for incident RP beam (a) with Au, Cu coating metals and (b) with Al, Ni coating metals. The coating metals are Au, Cu, Ni, Al. The dielectric is glass ($\varepsilon_1/\varepsilon_0 = 2.25$). The distance $l$ is varied from 0nm to 600nm under the condition that the other parameters of the shape are kept constant ($d \approx 27.4\text{nm}$, $R = 712\text{nm}$, $h = 1652\text{nm}$).
Figure 3.6: The maximum of optical intensity at the tip $|E|^2$ for incident RP beam (a) with Au, Cu coating metals and (b) with Al, Ni coating metals. The dielectric is glass ($\varepsilon_1/\varepsilon_0 = 2.25$). The distance $l$ is varied from 0nm to 600nm under the condition that the other parameters of the shape are kept constant ($d = 27.4\text{nm}$, $R = 712\text{nm}$, $h = 1652\text{nm}$)
For incident LP beam, the dependences of maximum enhanced optical intensities on the distance $l$ are shown in Fig. 3.6(a) and (b). We can see that the enhanced optical intensity at the tip cannot be realized for the symmetric probe ($l=0$ nm). For the case of incident LP beam, there is an optimum distance $l$ where the maximum optical intensity can be obtained at the tip of tilted conical probe for all coating metals.

**Table 3.1: The largest value of the maximum optical intensity for incident LP beam**

| Coating metal | $|E|^2_{\text{max}}$ | $l$(nm) |
|---------------|---------------------|--------|
| Au(-13.6-j1.08) | $5.7 \times 10^3$ | 290    |
| Cu(-11.6-j1.8) | $2.9 \times 10^3$ | 410    |
| Ni(-14.7-j9.9) | $1.7 \times 10^2$ | 430    |
| Al(-56.1-j20.9) | $1.4 \times 10^2$ | 450    |

The largest value of the maximum optical intensity $|E|^2_{\text{max}}$ and the optimum distance $l$ is shown in Table 1 for each coating metal. For Au, the largest maximum optical intensity can be obtained at the short distance $l$ compare with that for Cu, Al and Ni (See Table 1). We can see that optimum distance $l$ which gives the largest maximum intensity increases with the increase of the dissipation of metal. It means that the dissipation of the metal is an important factor to generate large enhanced optical intensity at the tip.

We show the results in Fig. 3.5(a) and 3.6(a) in the same intensity scale for Au metal coating in Fig. 3.7. The solid circles and open circles present the results of incident RP and LP beams, respectively. The value of maximum optical intensities for incident RP and LP beams are shown at $l = 350$ and $410$ nm in Table 3.2. From Fig. 3.7 and Table
3.2, we can see in the region of \( l < \sim 380 \text{ nm} \), the maximum optical intensities for incident RP beam are always larger than those for incident LP beam. In the region of \( l > \sim 380 \text{ nm} \), the maximum optical intensities for incident LP beam exceed those for incident RP beam. We can see the similar behavior for other coating metals from results in Fig. 3.5. This means that the RP beams does not always make larger optical intensity at the tip than that made by the LP beams in the tilted probe.

Figure 3.7: The maximum of optical intensity at the tip of Au-coating metal probe \( |E|^2 \) for incident RP beam and incident LP beam in the same intensity scale.
Table 3.2: The maximum optical intensities $|E|^2$ for incident RP and LP beams in the region of 350 nm < $l$ < 410 nm

<table>
<thead>
<tr>
<th>Distance l</th>
<th>350 nm</th>
<th>410 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP beam</td>
<td>$5.7 \times 10^3$</td>
<td>$3.0 \times 10^3$</td>
</tr>
<tr>
<td>LP beam</td>
<td>$5.0 \times 10^3$</td>
<td>$4.3 \times 10^3$</td>
</tr>
</tbody>
</table>

3.5 Dependence of maximum optical intensities on polarized angle

Finally, we examined the effect of changing the polarized angle $\beta$ (LP beam is propagating in the $z$-direction and its direction of polarization makes an angle of $\beta$ with the $x$ axis) on the maximum of optical intensity at the tip of probe for incident LP beam with Au metal coating.

For the incident LP Gaussian beam, the $x$, $y$, $z$ components of electric field at $z = 0$ can be written as:

$E_x(x, y, 0) = A \exp[-(r/w)^2] \cos \beta$

$E_y(x, y, 0) = A \exp[-(r/w)^2] \sin \beta$

$E_z(x, y, 0) = jA[2x/(k_0w^2)] \exp[-(r/w)^2]$
For the case under study, we chose the proposed tilted conical probe (distance \( l = 300 \) nm) and change the polarized angle \( \beta \) from \( 0^0 \) to \( 90^0 \).

![Graph showing optical intensity vs. polarized angle](image)

**Figure 3.9:** The maximum of optical intensity \( |E|^2 \) located at 2.5nm from the tip of the tilted probe \((l = 300 \text{ nm}, d \approx 27.4 \text{ nm}, R = 712 \text{ nm}, h = 1652 \text{ nm})\) for incident LP beam with Au metal coating depends on the polarized angle \( \beta \). In this simulation, the tilted probe has been kept constant while the polarized angle is changed from \( 0^0 \) to \( 90^0 \).

As shown in Fig. 3.9, the maximum optical intensity strongly depends on the polarized angle \( \beta \) of incident LP beam. We can see that the enhanced optical intensity at the tip can be realized for the case of \( \beta = 0^0 \). In the region of \( 0^0 < \beta < 45^0 \), the maximum of optical intensity at the tip decreases with the increase of the polarized angle. When \( \beta \) continues to rise in excess of \( 45^0 \), the maximum optical intensity change complicatedly. However, it is found that the most suitable characteristic is obtained for the case of \( \beta = 0^0 \).
3.6 Conclusion

The possibility of using metal-coated dielectric probe of tilted conical shape utilizing surface plasmon polariton (SPP) was demonstrated. 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 tilted shape (asymmetric shape) by the volume integral equation method. We consider the cases of incident radially polarized and linearly polarized Gaussian beams and found that the tilted SPP conical probe is valid for both incident LP and RP beams. The optical intensity at the tip of tilted metal-coated dielectric probe strongly depends on not only the degree of asymmetry but also the dissipation of coating metal for both incident RP and LP beams. Since the degree of the asymmetric shape and the coating metal of the probe affect significantly the maximum enhanced optical intensity at the tip for incident RP and LP beams, the findings of this study demonstrate that tilted conical probes must be carefully designed and fabricated.
Chapter 4

4. Analysis of SPP nanofocusing by asymmetric metal-coated dielectric probe: partial metal-coating

Abstract: For the purpose of developing the probe using surface plasmon polariton (SPP) nanofocusing that is valid for incident linearly polarized (LP) wave, the partially metal-coated dielectric conical probe is investigated numerically by the volume integral equation. It is found that it possible to perform SPP nanofocusing using this probe for incident LP Gaussian beam in addition to incident radially polarized (RP) beam. The basic characteristics of the strongly localized and enhanced optical near-fields on the tip of the probe and optical intensities inside the probe are investigated. For the incident LP beams, it is found that the optimum structure of the partially metal-coated dielectric probe exists. For the case of incident RP beam, partial metal-coating of the probe degrades the characteristic of nanofocusing, i.e., fully metal-coated conventional probe is the optimum shape for incident RP beam.

4.1 Introduction

Recent theoretical and experimental studies of nanometric integrated optical circuits that employ surface plasmon polaritons (SPPs) have shown that functional devices utilizing SPPs can be expected to play an important role in future of nanometric integrated optical circuits. For example, optical waveguide circuits based on SPPs can be miniaturized much further than conventional diffraction-limited optical waveguide circuits [1-8], opening up the possibility of developing nanometric integrated optical circuits.
In order to excite the surface plasmon polaritons into nanometric optical waveguide circuits, the optical waves generated by the laser source must be focused into the space whose size is much smaller than the wavelength, i.e., the nanosize space. The metal-coated dielectric probe can create the significantly localized and enhanced near-fields in the nanosized region near the tip. This focusing technique is often called SPP nanofocusing or superfocusing so far [9-16] and it has been applied to the optical probe of scanning near-field optical microscope (SNOM). The metal-coated dielectric probe of conical shape is one of fundamental devices in nanophotonics utilizing SPPs [9-16].

Recently plasmonic lasers that directly generate nanoscale light, essentially using electronic transitions as a focusing mechanism while also coherently sustaining it by amplification has been widely interested and will be a promising techniques of making nanosized optical electromagnetic fields [17]. However, SPP nanofocusing by the metal-dielectric probe is also useful due to low-cost and easy fabrication in the future.

The symmetric metal-coated dielectric conical probe is valid only for the incident radially polarized (RP) beam and is not valid for the incident linearly polarized (LP) beam. It is cumbersome to change the incident LP light to the RP light in the practical optical applications. Thereupon, the nanofocusing which is valid for the incident LP light is preferable in the practical applications because the polarization of dominant mode in the optical fiber is LP mode (HE11-mode), i.e., linearly polarized wave.

In order to perform the SPP nanofocusing of LP waves, a variety of structures have been studied and investigated [9-16]. The authors have also proposed the idea using metal-coated dielectric probe of tilted conical shape and have shown that this probe is valid for both incident LP and RP waves [14]. The idea of SPP nanofocusing by using
In this paper, in order to achieve the SPP nanofocusing for incident LP beam by the dielectric conical probe, another asymmetric structure of the probe, i.e., the partially metal-coated dielectric probe is proposed. We can consider that partially metal-coating also destruct the interference cancellation among SPPs on the tip.

In the present study, the volume integral equation (VIE) is used to simulate the problem numerically [7, 8, 13, 16] and show that the proposed probe can achieve the SPP nanofocusing for both incident LP and RP beams. We first show the configuration of the partially metal-coated dielectric probe. Then we solve the scattering problem by VIE and show the dependences of the maximum enhanced local optical intensities on the tip on the degree of the asymmetry of the partially metal-coated dielectric probe. By showing optical intensities inside the probe, we finally investigate the difference of the optical intensity distributions inside the probe between incident LP and RP beams.

4.2 Geometry of the partially metal-coated dielectric probe

We consider the partially metal-coated dielectric probe shown in Fig. 4.1. The conical dielectric probe has a base radius $R$ and is made of a dielectric with a permittivity $\varepsilon_1$ fabricated in the $(x, y, z)$ coordinate system shown in Fig. 4.1. The surrounding free space has a permittivity $\varepsilon_0$. The conical probe has a height of $h$. The side of conical dielectric probe is partially coated with the metal with a permittivity $\varepsilon_2$ and thickness of $d$.

In Fig. 4.1, we can see that the probe consists of two parts i.e., the dielectric with covered metal-coated layer and the original dielectric without coating metal. We notice
that the shape of the partially metal-coated conical dielectric probe is rotationally symmetric about z-axis in Fig. 1. However, the distribution of the dielectric permittivity is not rotationally symmetric due to the partial metal-coating.

We consider that the metal-coating is cut by a plane parallel to the \( y-z \) plane (cut plane) shown in Fig. 4.1. In order to define the degree of the asymmetry of the partially metal-coated probe, we use the ratio between \( l \), which is the distance between the cut plane and the z-axis shown in Fig. 1(a), (c) and (d), and base radius \( R \), i.e., \( l/R \). The case of \( l/R=1 \) corresponds to the fully metal-coated symmetric probe, the case of \( l/R=0 \) corresponds to the half metal-coated asymmetric probe and other cases of \( 0 < l/R < 1 \) correspond to the partially metal-coated asymmetric probes.
Figure 4.1: Geometry of the partially metal-coated conical dielectric probe. (a) The conical structures have a base-radius $R$ and a height $h$. The metal coating has a thickness $d$. Permittivity of the surrounding free space, the coating metal, and the dielectric in the probe are denoted by $\varepsilon_0$, $\varepsilon_1$ and $\varepsilon_2$, respectively. Degree of the asymmetry of the probe is characterized by distance $l/R$. The axis of linearly and radially polarized Gaussian beams coincides with $z$-axis and beams are normally incident on base of the probe circle from the region $z < 0$. The cross sections of the asymmetric probe are shown on (b) $z$-$y$ plane, (c) $z$-$x$ plane and (d) $x$-$y$ plane.
4.3 Volume Integral Equation

We first divide three dimensional models of the probe into tiny cubes having dimensions of $\delta \times \delta \times \delta$ to solve the scattering problem. Then, we discretize the volume integral equation (VIE) by the method of moments using roof-top functions as basis and testing functions in each cubes and finally solve the resultant system of linear equations numerically by the iteration method called generalized minimum residual (GMRES) with Fast Fourier Transformation (FFT). We consider two cases of incident beam in this paper, i.e., the LP and RP Gaussian beams. Both beams, whose axis coincides with z-axis, are assumed to be incident along the z-axis from negative z direction. For the LP Gaussian beam which is polarized in the x-direction, the x, y, z components of electric field at $z = 0$ can be written as [18];

\begin{align*}
E_x(r, 0) &= A \exp\left[-\left(\frac{r}{w}\right)^2\right] \\
E_y(r, 0) &= 0 \\
E_z(r, 0) &= jA \left[2x/(k_0w^2)\right] \exp\left[-\left(\frac{r}{w}\right)^2\right]
\end{align*}

(4.1)

The radial and $z$ components of electric field of the incident RP Gaussian beam at $z = 0$ can be written as [19];

\begin{align*}
E_r(r, 0) &= 2A(r/w) \exp[-(r/w)^2] \\
E_z(r, 0) &= -\frac{jA}{k_0w} \left[1 - \left(\frac{r}{w}\right)^2\right] \exp[-(r/w)^2]
\end{align*}

(4.2)

In Eqs.1 and 2, $k_0$ is the wavenumber in the free space, $w$ is the spot size of the beam and $r = (x^2 + y^2)^{1/2}$. The beam amplitude is given by $A=1$ in Eqs. 4.1 and 4.2 and both LP and RP beams have the same incident energies at $z = 0$. The LP and RP optical fields excite SPPs along the partially metal-coated surface of the probe. The optical
Chapter 4 Partially metal-coated dielectric probe

Fields of the SPPs are focused by decreasing the cross section of the probe along the propagation direction and make the strongly localized and enhanced fields on the tip. Through this paper, the wavelength \( \lambda \) is 633 nm and the sized of discretized cube \( \delta \) is given by \( k_0 \delta = 0.05 \) (\( \delta = 5 \) nm). The beam spot size of is given by \( w = \lambda \) at \( z = 0 \).

4.4 Partially metal-coated dielectric conical probe

We show an idealized mathematical model of typical conical structure shown in Fig. 4.1, a base radius of \( k_0 R = 7.07 \) (\( R = 712 \) nm) and a height of \( k_0 h = 17.3 \) (\( h = 1743 \) nm) and the whole structure is discretized by the tiny cubes. The metal coating is a gold (Au) whose relative permittivity is given by \( \varepsilon_2 / \varepsilon_0 = -13.8 - j1.08 \) and that of the dielectric is given by \( \varepsilon_1 / \varepsilon_0 = 2.25 \). The average thickness of the metal-coating is given by \( k_0 d = 0.27 \) (\( d = 27.4 \) nm).

It is known that optical intensity near the tip is very sensitive to the shape of the tip [12, 15]. So, we consider two kinds of shapes of the tip whose arrangement of cubes in the top 14 and 13 layers parallel to the \( x-y \) plane of the probe are shown in Fig. 4.2(a) and (b), respectively. We call probe having tip-shape shown in Fig. 4.2 (a) and (b) probe-1 and probe-2, respectively. The difference between probe-1 and probe-2 is the existence of only one cube in the top layer of the probe. In the probe-2, one cube is removed in the top layer from that of probe-1. We can consider that probe-2 has a larger radius of curvature at the tip than that of probe-1.

The whole discretized structure of probe-1 is composed of 346 layers with thickness \( \delta \) parallel to the \( x-y \) plane and that of probe-2 is composed of 345 layers. The inset in Fig. 4.2 shows the tiny cubes having dimensions of \( \delta \times \delta \times \delta \) used for solving the scattering.
problem shown in Fig. 1 by the VIE.

Figure 4.2: The arrangement of cubes in the top 14 layers of (a) probe-1 and those in the top 13 layers of (b) probe-2. The inset shows the tiny cube with \( \delta \times \delta \times \delta \) dimensions.

4.5 Nanofocused optical intensities by the linearly polarized beam

In order to solve the scattering problem shown in Fig. 4.1, the three-dimensional rectangular region including free space and the probe are divided into tiny \( 317 \times 317 \times \)
377 cubes. Since the unknowns are the three components of electric flux on the boundaries of each tiny cube [10], the total number of unknowns of the system to be solved is about 155 millions. The computational time in solving one case (one point in Fig. 4.3) of the partially metal-coated probe by VIE+GMRES+FFT are about six hours by the supercomputer system in Nagoya University.

The dependences of the nanofocused maximum optical intensity in free space on the degree of the asymmetry of the probe, i.e., the ratio $l/R$ are shown in Fig. 4.3 for incident LP beam. The maximum intensity in free space exists on the plane $\delta/2$ apart above the top cube in our numerical simulations. In Fig. 4.3, the values of $l/R$ are changed from 0 to 1 while keeping the other parameters of the probe. The open circles indicate the results of probe-1 and the solid circles indicate the results of probe-2.
Figure 4.1: Partially metal-coated dielectric probe results

(a) Probe 1

(b) Probe 2
Figure 4.3: The dependence of the maximum optical intensity on the degree of asymmetry of the probe, i.e., $l/R$ for incident LP beam with (a) for probe-1, (b) for probe-2, (c) comparing probe-1 and probe-2. Intensity distributions of $l/R$ indicated by arrows will be shown in Fig. 4.4.

The results in Fig. 4.3 reveal that, for the incident LP beam, we can see that the localized and enhances optical fields on the tip can become $\sim 10^3$ times larger than that of the incident intensity by the partially metal-coated dielectric conical probe shown in Fig. 4.1. It is interesting that the optimum value of $l/R=0.41$ can be obtained in the results shown in Fig. 4.3. The optical intensities of the probe-1 are about 2.5 times larger than those of the probe-2 in the whole range of values of $l/R$. It is interesting that
only one tiny cube on the top layer can realize the significant enhancement of the optical intensity above the top cube. In Fig. 4.3, we can see that there is no nanofocusing for the case of $l/R=1.0$, i.e., fully metal-coated symmetric probe.
Figure 4.4: Typical intensity distributions $|E(x, 0, z)|^2$ of probe-1 on the x-z plane in Fig. 4.1 for incident LP beam for the case of (a) $l/R=0$, (b) $l/R=0.14$, (c) $l/R=0.25$, (d) $l/R=0.41$, (e) $l/R=0.73$ and (f) $l/R=0.91$. The values of $l/R$ of (b), (c), (d), (e) and (f) correspond to the position indicated by arrows in Fig. 4.3. The scale range of the intensity is 0.0-5.0.
The typical optical intensity distributions $|E(x, 0, z)|^2$ of tip-1 on the x-z plane are shown in Fig. 4.4 for the case of (a) $l/R=0.0$, (b) $l/R=0.14$, (c) $l/R=0.25$, (d) $l/R=0.41$, (e) $l/R=0.73$ and (f) $l/R=0.91$ and these values of $l/R$ are indicated by the arrows with same alphabets as used in Fig. 4. In Figs. 4.4 (a)-(d) (the range from $l/R=0$ to $l/R=0.41$), the intensity distributions near the tip change significantly with the change of values of $l/R$. This means constructive and destructive interference is critical factor to the enhance intensity on the tip.
Chapter 4 Partially metal-coated dielectric probe

(b) $l/R = 0.73$

(c) $l/R = 0.91$
Figure 4.5: Optical intensity distributions $|E(0, 0, z)|^2$ for incident LP beam along the z-axis for the case of (a) $l/R=0.41$ (open circle), (b) $l/R=0.73$ (solid circle), (c) $l/R=0.91$ (cross) and (d) to compare 3 cases of $l/R$. The optical intensities between two dotted lines show those inside coating metal.

In order to see the change of enhanced intensities inside the probe in detail, the intensity distributions along z-axis $|E(0, 0, z)|^2$ are shown in Fig. 4.5 for incident LP beam for the case of $l/R=0.41$, $l/R=0.73$ and $l/R=0.91$ ((d)-(f) in Fig. 4.4). The region of $0 < z < 1687$ nm is interior of the dielectric region in Fig. 4.5. The intensity distributions in this region do not change by changing the values of $l/R$. The region $1687$ nm $< z < 1738$ nm sandwiched by the two dotted lines in Fig. 4.5 is the interior of the coating metal. In the region of inside the metal, intensity distributions are strongly depend on the values of $l/R$. The rapid increase and decrease of the intensity inside the metal are due to the constructive interferences for the case of $l/R=0.41$ and $l/R=0.73$, and
destructive interference for the case of $l/R=0.91$ among SPPs propagating along the coating metal. The range $1738<z$ is the free space above the tip in Fig. 4.5 and intensities decrease rapidly with the increase of the distance from the tip.

The intensity distributions are discontinuous across the boundaries between dielectric and metallic regions (the position indicated by the left dotted line in Fig. 4.5) and between metal and free space regions (the position indicated by the right dotted line in Fig. 4.5), because electric field components normal to the surfaces of the cubes are discontinuous across the boundary between two cubes of different dielectric.

4.6 Nanofocused optical intensities by the radially polarized beam

The partially metal-coated dielectric probe is also valid for incident RP beam. In order to know the difference of the results between incident LP and RP waves, we calculate same characteristics for incident RP beam as those shown in Figs. 4.3-5. In the case of incident RP beam, the dependences of the maximum optical intensity on the tip on the ratio $l/R$ are shown in Fig. 4.6. It is found that the enhanced intensities can become $\sim 10^4$ times larger than those of incident beam and this value about ten times larger than that of incident LP beam. It is also found that the fully metal-coated probe ($l/R=1$) is the optimum for incident RP beam and that the enhanced intensity of probe-1 is about three times larger than that of probe-2.
Figure 4.6: (a) The dependence of the maximum optical intensity at the tip on the degree of partial coating $l/R$ for incident RP beam for probe 1.
Figure 4.6: (b) The dependence of the maximum optical intensity at the tip on the degree of partial coating $l/R$ for incident RP beam for probe 1 and probe 2. Intensity distributions of $l/R$ indicated by arrows are shown in Fig. 4.7.

The typical optical intensity distributions $|E(x, 0, z)|^2$ of of tip-1 on the x-z plane for the case of $l/R=0.0$, $l/R=0.14$, $l/R=0.25$, $l/R=0.41$, $l/R=0.73$ and $l/R=0.91$ are shown in Fig. 4.7. These values of $l/R$ are same as those shown for the case of incident LP beam and they are shown by the arrows in Fig. 4.6. Compared results in Fig. 4.7 with those in Fig. 4.4, the intensity distributions near the tip do not change with the change of $l/R$, because only constructive interference occur for the case of incident RP beam.

The intensity distributions along z-axis $|E(0, 0, z)|^2$ are shown in Fig. 4.8 for incident RP beam for the case of $l/R=0.41$, $l/R=0.73$ and $l/R=0.91$. In these cases, the characteristics inside the metal $1687 \text{ nm} < z < 1738 \text{ nm}$ are similar for three cases. The
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rapid increases of the intensities inside the metal are due to the constructive interference among SPPs propageted along the coating metal and destructive interference does not occur. Compare the results in Fig. 4.8 with Fig. 4.5, we can also see that only constructtibe intereference ocur inside the metal for the case of incident RP beams.

Figure 4.7: Typical intensity distributions $|E(x, 0, z)|^2$ of tip-1 on the x-z plane in Fig. 4.1 for incident RP beam for the case of (a) $l/R=0$, (b) $l/R=0.14$, (c) $l/R=0.25$, (d) $l/R=0.41$, (e) $l/R=0.73$ and (f) $l/R=0.91$. Results in (b), (c), (d), (e) and (f) correspond to arrows shown in Fig. 4.4.
Figure 4.8: (a) Optical intensity distributions for incident RP beam along z-axis for the case of $l/R=0.41$

Figure 4.8: (b) Optical intensity distributions for incident RP beam along z-axis for the case of $l/R=0.73$
Figure 4.8: (c) Optical intensity distributions for incident RP beam along z-axis for the case of $l/R=0.91$

Figure 4.8: Optical intensity distributions for incident RP beam along z-axis for the case of (a) $l/R=0.41$ (open circle), (b) $l/R=0.73$ (solid circle) and (c) $l/R=0.91$ (cross). Intensities in region between two dotted lines show the intensities inside coating metal.
4.7 Conclusions

For the purpose of development of surface plasmon polariton (SPP) nanofocusing probe that is valid for linearly polarized incident waves, we examined the partially metal-coated dielectric probe in this paper. The basic characteristics of the maximum optical intensity on the tip created by SPP nanofocusing in the probe are investigated by the volume integral equation. We considered the cases of incident linearly polarized (LP) and radially polarized (RP) Gaussian beams. The intensity distributions of various structure of the probe are investigated. Although the intensities of enhanced fields on the tip for incident LP beams are smaller than those obtained by the incident RP beams, it is found that the partially metal-coated dielectric probe can create the localized and enhances intensity on the tip that is \( \sim 10^3 \) times larger than that of incident wave for incident LP waves.
Chapter 5

5. Conclusions

For the purpose of developing the probe using surface plasmon polariton (SPP) nanofocusing that is valid for incident linearly polarized (LP) wave, the asymmetric metal-coated dielectric conical probe is investigated numerically by the volume integral equation. It is found that it possible to perform SPP nanofocusing using this probe for incident LP Gaussian beam in addition to incident radially polarized (RP) beam. The basic characteristics of the strongly localized and enhanced optical near-fields on the tip of the probe and optical intensities inside the probe are investigated. For the incident LP beams, it is found that the optimum structure of the partially metal-coated dielectric probe exists. For the case of incident RP beam, partial metal-coating of the probe degrades the characteristic of nanofocusing, i.e., fully metal-coated conventional probe is the optimum shape for incident RP beam.

This dissertation is composed of four chapters. Chapter 1 was an introduction of surface plasmon polariton, how to exciting surface plasmon polaritons into nanometric optical waveguide circuits, motivation for this work as well as an overview of the components of this dissertation.

Chapter 2 presented the theory for calculation of propagation constant and the field distribution of a waveguide problem. We discretize the volume integral equation (VIE) by the method of moments using roof-top functions as basis and testing functions in
each cubes and finally solve the resultant system of linear equations numerically by the iteration method called generalized minimum residual (GMRES) with Fast Fourier Transformation (FFT).

Chapter 3, by the volume integral equation method, the metal-coated dielectric probes of tilted conical shape were investigated for nanofocusing of surface plasmon polaritons. We consider the cases of incident radially polarized and linearly polarized Gaussian beams and found that the tilted SPP conical probe is valid for both incident LP and RP beams. The optical intensity at the tip of tilted metal-coated dielectric probe strongly depends on not only the degree of asymmetry but also the dissipation of coating metal for both incident RP and LP beams.

Chapter 4, for the purpose of developing the probe using surface plasmon polariton nanofocusing that is valid for incident linearly polarized (LP) wave, the partially metal-coated dielectric conical probe is investigated. We considered the cases of incident linearly polarized (LP) and radially polarized (RP) Gaussian beams. The intensity distributions of various structure of the probe are investigated. Although the intensities of enhanced fields on the tip for incident LP beams are smaller than those obtained by the incident RP beams, it is found that the partially metal-coated dielectric probe can create the localized and enhances intensity on the tip that is $10^3$ times larger than that of incident wave for incident LP waves.

Since the degree of the asymmetric shape and the coating metal of the probe affect significantly the maximum enhanced optical intensity at the tip for incident RP and LP beams, the findings of this study demonstrate that tilted conical probes must be carefully designed and fabricated.
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