Laser field distribution near inclined taper optical antenna

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Abstract. This work focuses on the mechanism of laser field enhancement within a gap between a taper plasmonic nanoantenna and a dielectric substrate in the inverted optical configuration. We show that field enhancement factor depends on several parameters such as: tip-sample distance, radius of curvature of the tip and its inclination angle in respect to the substrate. In particular, a relation between the field enhancement near the tip apex and the inclination angle is deduced. Numerical simulation and optimization were performed within the framework of the FDTD method and the Green function formalism.

1. Introduction

In the recent years, there has been great interest in optical antennas design [1]. Optical antenna is a device that converts freely propagating radiation into localized modes and vice versa [2]. Optical antennas allow one to probe a sample at a subwavelength scale via different optical near-field microscopy techniques [3]. One of the methods is, for example, tip-enhanced Raman scattering (TERS), which provides a non-destructive chemical analysis of subwavelength structures in the visible range under normal conditions. In this method the nanoantenna is positioned by a distance of several nanometers above the sample surface in highly focused laser field, providing amplification of interaction between optical radiation and matter, as well as strong localization of electromagnetic field [4].

One of the goals of the optical near-field microscopy is an increase of field enhancement and concentration via optical antenna design. Recent results have been obtained using different physical phenomena that help to reach the highest electric field enhancement, for example, scanning probe microscopy [6,7,9] or scanning tunneling microscopy [5,8]. The optical resolution of ~2 nm was obtained in the experiment with the use of ultra-low temperature and ultra-high vacuum [5]. In the Ref. [6,7] optical resolution of several nanometers was obtained under normal conditions, but with the use of additional processes.

Sub-10 nm optical resolution may be achieved by additional effects. In Ref.[10,11], for example, there were performed experiment and simulation of the excitation of surface plasmon polaritons on a metal grid side surface of the probe and the adiabatic compression near the tip.

In this paper we describe physical effects that occur in tip enhanced near-field optical microscopy when inclined tip is used. This method is practically feasible and meaningful; via this method we can increase the gain of the optical response of the sample and increase optical resolution, and make steps towards the development of new devices using the phenomenon of surface and localized plasmon resonances in optical near-field interaction for processing and transmitting information. We show that inclined tips application provides high concentration of energy and enhancement of intensity larger
than in use of vertical probe. The relation between the field intensity enhancement and the angle of inclination in XZ-plane by using finite-difference time-domain simulation is analyzed in detail. Our aim is to study physical effects that occur in the process of scattering of highly focused laser light with the inclined tip that is positioned by a distance of several nanometers above the substrate surface.

![Figure 1](image)

**Figure 1.** Tip orientation relatively to the optical z-axis: (a) 0°; (b) at θ angle [12].

2. Results and discussion

Figure 1(b) shows the schematics of the problem. To find the relation between the electric field intensity near tip apex and the angle of inclination of tip we use the Green’s function formalism described in Ref [13-15]. A total electric field scattered with a metallic nanosphere with a radius ρ, which is placed at the distance Δ from the planar interface between two dielectric media with dielectric constants ε1 and ε2, reads as

$$E(r, ω) = E_0(r, ω) + \frac{ω^2}{ε_0 c^2} \mathbf{G}_0(r, r_0; ω)α_{\text{eff}} E_0(r_0, ω),$$  

(1)

here $E_0$ is incident laser field, $ω$ is an angular frequency of the incident radiation, $\mathbf{G}_0(r, r_0; ω)$ is the Green’s function in free space and $α_{\text{eff}}$ is effective polarizability of inclined tip which determines the influence of the image field from the dielectric interface as in the expression [16]:

$$p_{\text{eff}} = α[E_0 + E_{\text{image}}] = α_{\text{eff}} E_0,$$  

(2)

here $E_{\text{image}}$ is a local field of the image dipole, which can be written as

$$E_{\text{image}} = \frac{1}{4πε_0} \left( \frac{3(p_{\text{eff}} (r_0' - r_0))(r_0' - r_0)}{|r_0' - r_0|^3} - \frac{p_{\text{eff}}}{|r_0' - r_0|^3} \right),$$  

(3)

where $r_0'$ is a vector position of an image dipole.

The polarizability of the small metallic sphere $α$ in Eq. (2) could be written as [17]
\[ \alpha = 4\pi\varepsilon_0\rho^3 \begin{pmatrix} \frac{\varepsilon_m - 1}{\varepsilon_m + 2} & 0 & 0 \\ 0 & \frac{\varepsilon_m - 1}{\varepsilon_m + 2} & 0 \\ 0 & 0 & \frac{f_c}{2} \end{pmatrix}, \] (4)

Here \( f_c \) is a complex field enhancement factor depending on tip material and geometry, \( \varepsilon_m \) is a dielectric function of the sphere. Since \( \alpha_{xx} \) and \( \alpha_{yy} \) components of the polarizability tensor much less than \( \alpha_{zz} \) component, in our approach we make the approximation \( \alpha_{xx} = \alpha_{yy} = 0 \).

Then longitudinal effective polarizability of inclined tip reads as

\[ \alpha_{\|}^{\text{eff}} = \frac{2\pi\varepsilon_0\rho^3 f_c \cos \theta'}{1 + \rho^3 b f_c (1 - 3 \cos^2 \theta)} \frac{\cos (\theta' - \gamma)}{16(\Delta + \rho)^3}, \] (5)

where \( b = \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + \varepsilon_1} \) is a quasi-static Fresnel-reflection coefficient, \( \theta \) is an angle of inclination of the probe, \( \theta' \) is an angle between the electric field and the probe symmetry axis. Analytic angular dependence of the electric field appears due to the presence of the non-diagonal components in polarizability tensor of the optical antenna rotated in the space which depend on the angle of inclination. There is an enhancement of the only field projection on the probe symmetry axis (approximately true), so the polarizability tensor has only one component of a nonzero in its own coordinate system. Changes in the local fields caused by the substrate are equivalent to the modification of tip polarizability.

One of the experimental schemes in near-field imaging is the inverted optical configuration, in which the sample is illuminated with laser beam propagating normally to the sample surface (Z-axis) is strongly focused near planar surface of the sample. Strong focusing of the beam is provided by use of immersion objective lenses with \( NA > 1 \) [18]. Herewith there are the regions in the focal where the field is polarized longitudinally (along the beam propagation direction), referred to as lobes [19]. Their quantity, their pattern and their field intensity are dependent on the numerical aperture, the polarization and the mode of the incident laser beam. If the beam is linearly polarized there are two regions in the focal plane located along the polarization axis [18].

Since the antenna mainly interacts with longitudinal lobes near vicinity of the tip we may drop X- and Y-components for the scattered field in tip’s own coordinate system. In this case we substitute \( |r - r_0| = \Delta + \rho \). Neglecting the contribution of the external field \( E_0 \) compared to the enhanced field, we find the field in the vicinity of the tip apex:

\[ E(r_0, \omega) = \frac{f_c \cos \theta'}{1 + \rho^3 b f_c (1 - 3 \cos^2 \theta)} \frac{E_0(r_0, \omega)e^{-ik \rho}}{16(\Delta + \rho)^3}. \] (6)

Since the value of the external field (the magnitude of the vector) the same in the right and left lobes, the ratio of the intensities at the maximal power:

\[ \left| \frac{E_{L,\text{max}}}{E_{R,\text{max}}} \right|^2 = \frac{\cos^2 \theta'_0}{\cos^2 \theta'_2} = \frac{\cos^2(\eta_1 - \theta)}{\cos^2(\pi - \eta_1 - \theta)}, \] (7)
where $\eta_1$ is the parameter corresponding to the inclination angle of the electric field vector to the normal of the focal plane in the points of intensity maxima of the lobes.

Series of FDTD simulations were carried out for different inclination angles and positions of gold probe - scanning of the focal field along the axis of field polarization (X axis) with the increment of 10 nm. For this purpose we used the following tip parameters: tip apex curvature radius $\rho = 13 \text{ nm}$, the apex angle $\alpha = 30^\circ$, tip-substrate distance $\Delta = 3 \text{ nm}$. Frequency of the incident light was $f = 450 \text{ THz}$ (in the resonance band of gold), the numerical aperture $NA = 1.4$. For numerical simulation the dielectric function of gold was taken from Ref. [20].

Figure 2 shows the results of parametric FDTD modeling of the ratio of maximum intensities in lobes on the probe angle.

![Field enhancement vs tip position](image)

**Figure 2.** Field enhancement vs tip position when tip inclination of 0° (a) and 35° (b). Maximal field enhancement vs tip inclination (c). The ratio of the intensities in two lobes (left to right) vs inclination angle (d) (solid red line is an approximation with Eq. (7)).

For the purposes of our approximation we state *a priori* the final relation between the maximum intensity in two lobes and the angle of the probe in the form of Eq.(7). It is shown that the lobes are shifting to the right while the right lobe decreases in intensity and becomes difficult to distinguish at angles greater than 40°. Approximation gives the estimated value of the parameter $\eta_1 = 34^\circ$. This means that at a this angle of inclination of the axis of the probe tip is oriented along the field vector.
direction and at the angle of $90 - 34 = 56^\circ$ the right lobe disappears, and amplification of transverse component of the field occurs at large angles predominantly. Thus, the critical angle at which one of the lobes disappears with given parameters of the problem ($NA = 1.4, f = 450\,\text{THz}$) is obtained roughly equal to $56^\circ$.

3. Conclusion
We have studied effects of the field enhancement beneath metallic tapered optical antenna that is inclined in respect to the substrate. We have simulated an optical response of the inclined optical antenna and the relation between the field enhancement near the tip apex and inclination angle was found. In particular we have shown that the laser field lobe shifts towards the optical axis and becomes spread. Thus, asymmetric energy distribution behavior is observed. This phenomenon explains why even upright probe retained small asymmetry of enhancement in the lobes, because ideally upright clutch of the optical antenna to a tuning fork is impossible.

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