Antenna and Plasmonic Properties of Scanning Probe Tips at Optical and Terahertz Regimes

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Abstract

A wide variety of near-field optical phenomena such as apertureless near-field scanning microscopy (ANSM) at optical and terahertz (THz) regimes and surface enhanced Raman scattering relies on the electric field enhancement at the end of a sharp tip. Achieving and controlling this electric field enhancement is a key challenge for a wide range of applications such as surface modification, data storage and optical tweezing at the nano-scale.

In this work, the metal tip is modeled as a gold semi-ellipsoid illuminated by two different excitation frequencies at optical and THz regimes with the wavelength of 630 nm and 0.3 mm respectively. The illumination is modeled as a plane wave field polarized parallel with respect to the tip axis. The dependence of electric field enhancement on apex radius, tip-sample distance and materials, tip geometry and radiation wavelength at optical and THz regimes is investigated. The antenna and plasmon resonances of a metal tip are calculated. Our calculation shows the competition between antenna and plasmon resonances and associated dephasing effects for the field enhancement at optical and THz regimes.

First, Maxwell's equations are solved in the frequency domain and the reliability of the finite element method (FEM) using COMSOL Multiphysics® software is checked by calculating the electric field enhancement on a gold tip and a glass sample with a tip-sample distance of 5 nm (Figure 1). The results are compared with both analytical solutions and the finite-element time-domain method (FETD).

Then the relationship between geometry, dephasing effects, antenna and plasmon resonances is shown. The existence of plasmon resonance at optical regime helps to increase field enhancement whereas, at THz regime, it is the antenna resonance which contributes to a strongly confined near field at the metal tip apex.

When the size of the metal tip is larger than approximately 0.4 λ (λ= 630 nm is the radiation wavelength), the field enhancement is less than 10 due to the dephasing effect (Figure 2). This is in contrast to THz radiation (λ= 0.3 mm) where the antenna effect is dominant leading to an extremely high field enhancement due to the antenna resonance effect. This is due to the fact that THz frequencies cannot excite Plasmon resonances, dephasing effects are thus minimized.

Reference

1. Katrin Kneipp et al., Surface-Enhanced Raman Scattering, Springer 2006.

2. Nastaran Kazemi-Zanjani et al., Localized enhancement of electric field in tip-enhancement Raman spectroscopy using radially and linearly polarized light., optical society of America, Vol. 21, No. 21 (2013).

3. Yeves C. Martin et al., Strength of the electric field in apertureless near-field optical microscopy, Journal of applied physics, Vol. 89, No. 10 (2001).

4. Anders Pros et al., Scaling in light scattering by sharp conical metal tips, Optics letters, Vol. 39, No. 11 (2014).

5. H. Tanoto et al., Greatly enhanced continuous-wave terahertz emission by nano-electrodes in a photoconductive photomixer, Nature photonics, Vol. 6 (2012).

6. A. J. Huber et al., Terahertz near-field nanoscopy of mobile carriers in single semiconductor nanodevices, Nano letters, Vol. 8, No. 11 (2008).

7. Nicolas Behr et al., Optical antenna properties of scanning probe tips: plasmonic light scattering, tip-sample coupling, and near-field enhancement, J. Phys. Chem, 112 , 3766-3773 (2008).

8. Kanglin Wang and Daniel M. Mittleman, Antenna effects in terahertz apertureless near-field optical microscopy, Applied physics letters, Vol. 85, No. 14 (2004).

9. Markus Walther et al., emission and detection of terahertz pulses from a metal-tip antenna. J. Optic. Soc. Am. B, Vol. 22, No. 11 (2005).

10. A. Cvitkovic et al., analytical model for quantitative prediction of material contrasts in scattering-type near-field optical microscopy, Optical society of America, Vol. 15, No. 14 (2007).

Figures used in the abstract

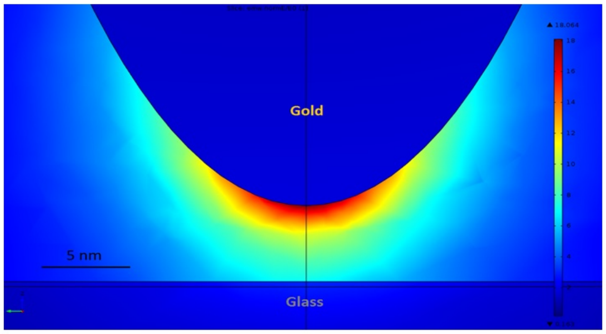

Figure 1: Spatial distribution and field enhancement for Au tip and glass substrate with apex radius of 10 nm and tip-sample distance of 5 nm.

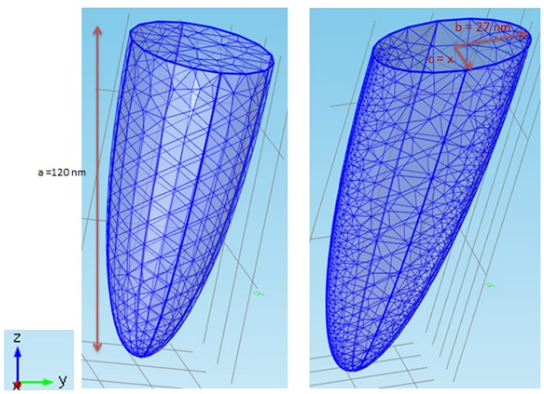

Figure 2: a) 3-D semi-ellipsoid tip apex with apex radius of 10 nm ; b) The tip is compressed in the yz plane. The b side of the ellipsoid is kept constant and the c side is variable to change the apex radius.

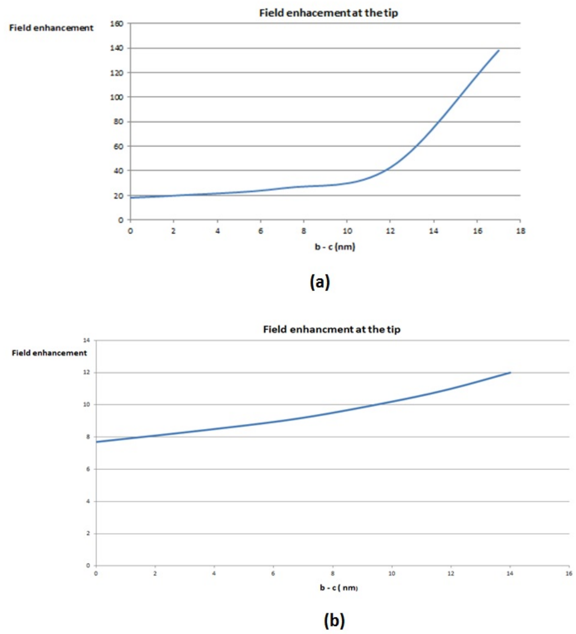

Figure 3: Field enhancement for Au tip and glass substrate with apex radius of 10 nm and tip-sample distance of 5 nm at a) optical regime and b) THz regime.

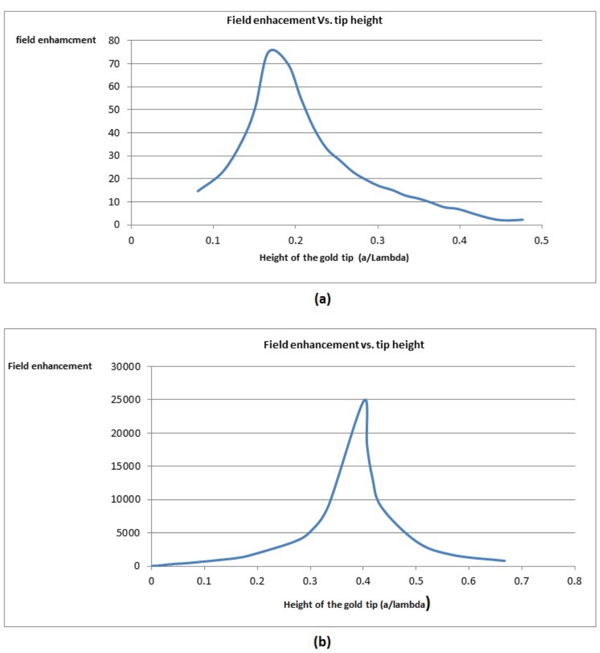

Figure 4: Field enhancement at a) optical regime with λ=630 nm and b) THz regime with λ=0.3 mm.