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

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Introduction:

Electric field enhancement at the end of a sharp tip is of crucial importance for near field scanning microscopy at optical and THz regimes as well as tip enhanced Raman scattering[1]. Thus, achieving and controlling this electric field enhancement is a key challenge for a wide range of applications.

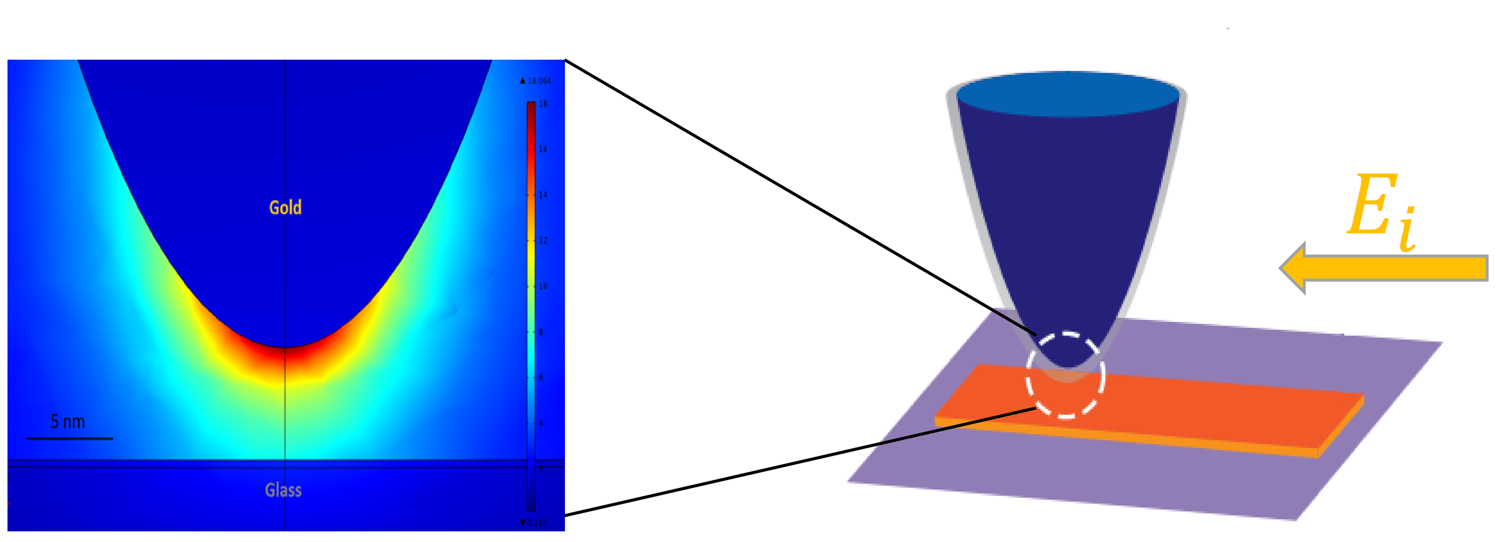


Figure 1. Illustration of 3-D hemi-ellipsoid as a tip apex illuminated with an incident plane wave for near field scanning microscopy.

Computational Methods:

- Solving Maxwell's equations with COMSOL RF module

$$\nabla \times (\mu_r^{-1} \times \boldsymbol{E}) - k_0^2 \left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)\boldsymbol{E} = 0$$

- Illuminating the model with λ_{opt} = 630 nm and λ_{THz} = 0.3 mm
- Dielectric constant of Au at optical and THz regimes

$$\varepsilon_{Optic} = -9.90 + 1.05\, i$$

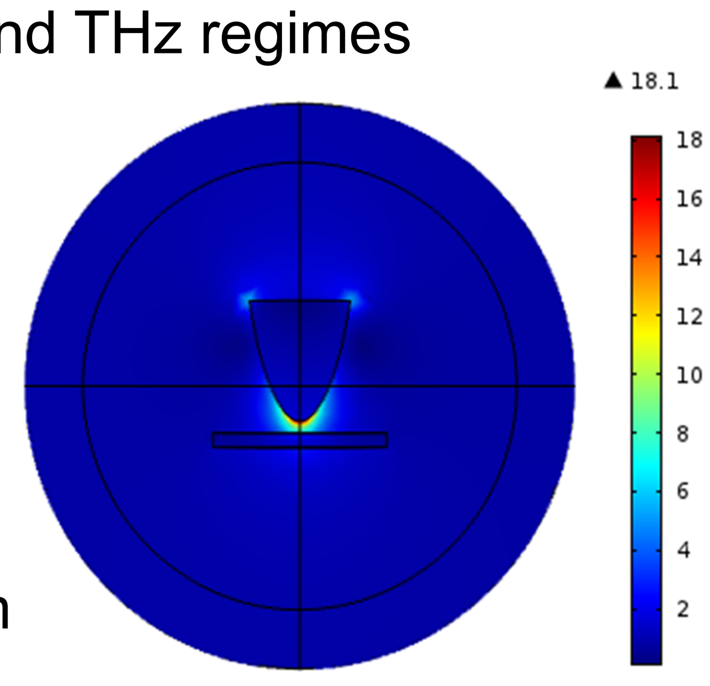
$$\varepsilon_{THz} = -1.4 \times 10^5 + 1.6 \times 10^6\, i$$

- Boundary conditions

  Perfectly matched layer

  Boundary layers to resolve skin depth

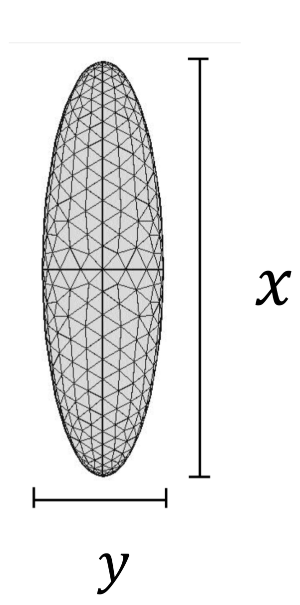
- User-controlled mesh with minimum mesh element of 10 nm



Analytical theory for full ellipsoid [3] :

$$\gamma = \left|\frac{\varepsilon}{1 + (\varepsilon - 1)A}\right|$$

$$A(r) = \frac{1}{2r^2}\int_0^{\infty} \frac{1}{(s+1)^{\frac{3}{2}}\,(s + r^{-2})}\, ds$$



- Both plasmonic and antenna effects are included
- Plasmon resonance when

$$Re\,[1 + (\varepsilon - 1)A] = 0 \;\text{ with }\; r = \frac{x}{y} = 3.2$$

COMSOL Multiphysics simulation for Au hemi-ellipsoid:

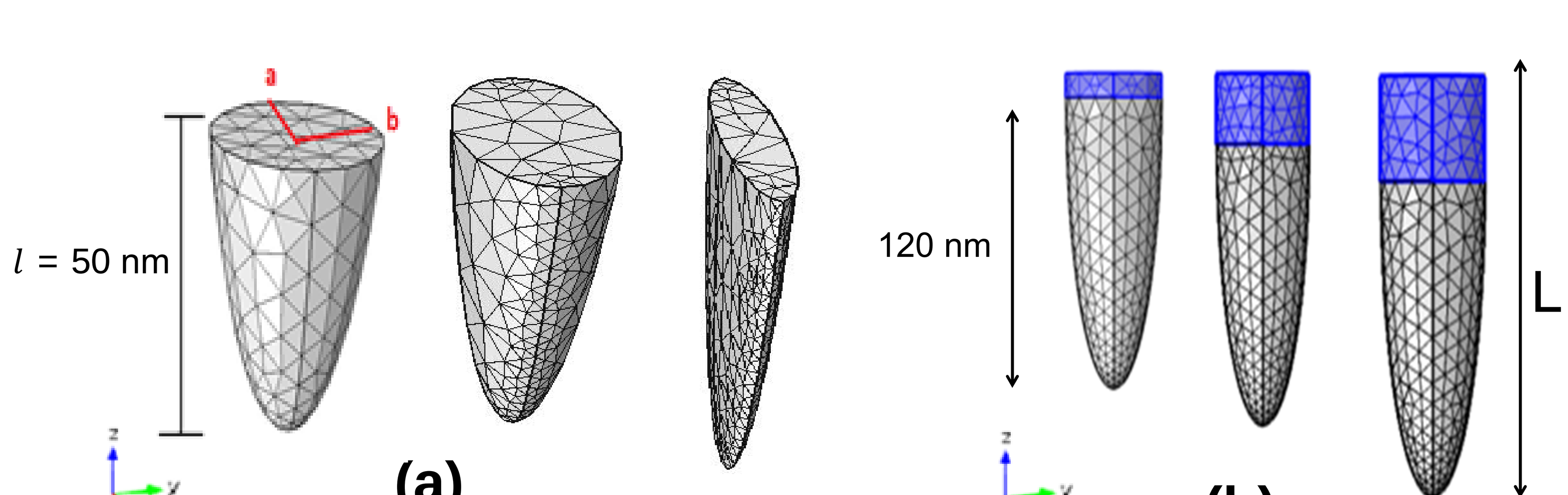


Figure 2. a) 3-D hemi-ellipsoid Au tip compressed in xz plane. b) Au 3-D cylinder shaft (blue) is added to 3-D Au hemi-ellipsoid.

Results:

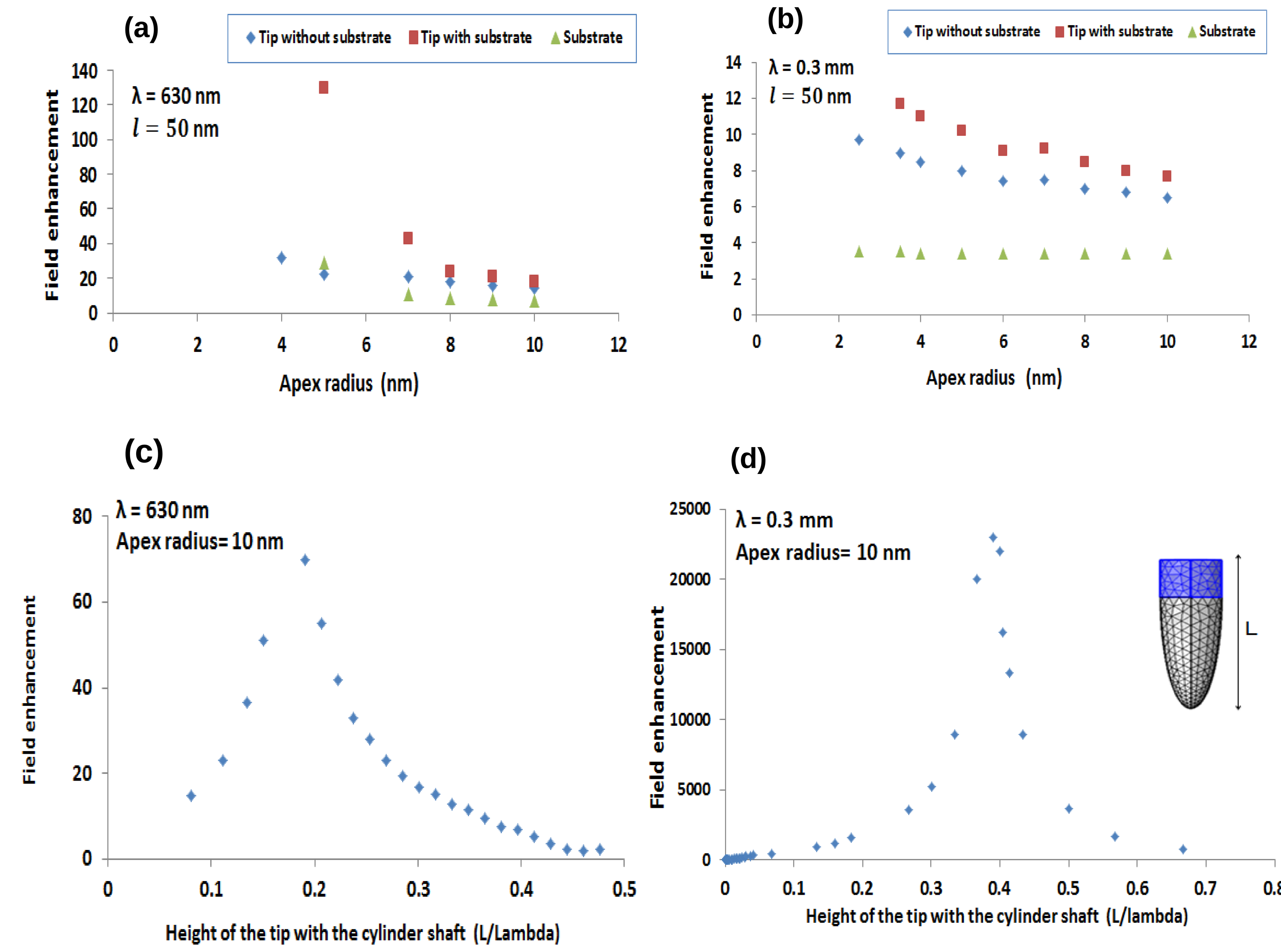


Figure 3. Dependence of field enhancement on the Au tip apex radius without substrate and with a glass substrate at a) optical and b)THz regimes with the tip-sample distance of 5 nm. Dependence of field enhancement on the height of the tip with the cylinder shaft added (L) at optical (c) and THz (d) regimes.

Conclusions:

- Non-linear and almost linear dependence of electric field enhancement on the Au tip apex radius at optical and THz regimes respectively
- The field enhancement is less than 10 due to dephasing effects when the Au tip is larger than approximately 0.4 λ at optical regime
- At THz regime, the antenna effect is dominant leading to an extremely high field enhancement
- Antenna effect has strong geometrical dependence
- For Au complete ellipsoid illuminated by λ= 630 nm, plasmon resonance can be obtained when r ≈ 3 – 3.5
- For Au hemi-ellipsoid illuminated by λ= 630 nm, plasmon resonance can be obtained when r ≈ 2
- COMSOL simulation agrees with the analytical results

References:

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