The Abdus Salam International Centre for Theoretical Physics

2328-11

Preparatory School to the Winter College on Optics and the Winter College on Optics: Advances in Nano-Optics and Plasmonics

30 January - 17 February, 2012

Optical antennas: Spectroscopy, Microscopy and other applications

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Optical antennas: Spectroscopy, Microscopy and other applications

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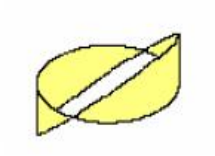
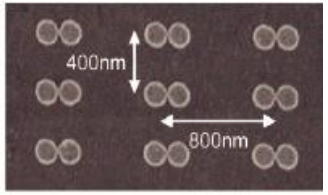
Winter College on Optics: Advances in Nano-Optics and Plasmonics
February 6-17, 2012
The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

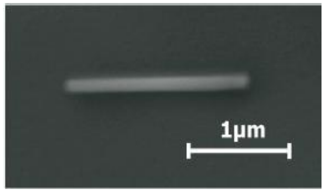
Outline

- Optical antennas: Basics

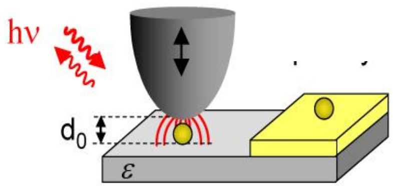




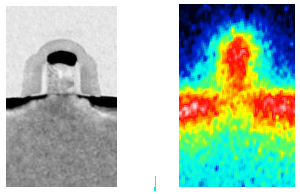
- Playing with antenna modes



- Optical antennas for Enhanced Spectroscopy: Coupling for SERS

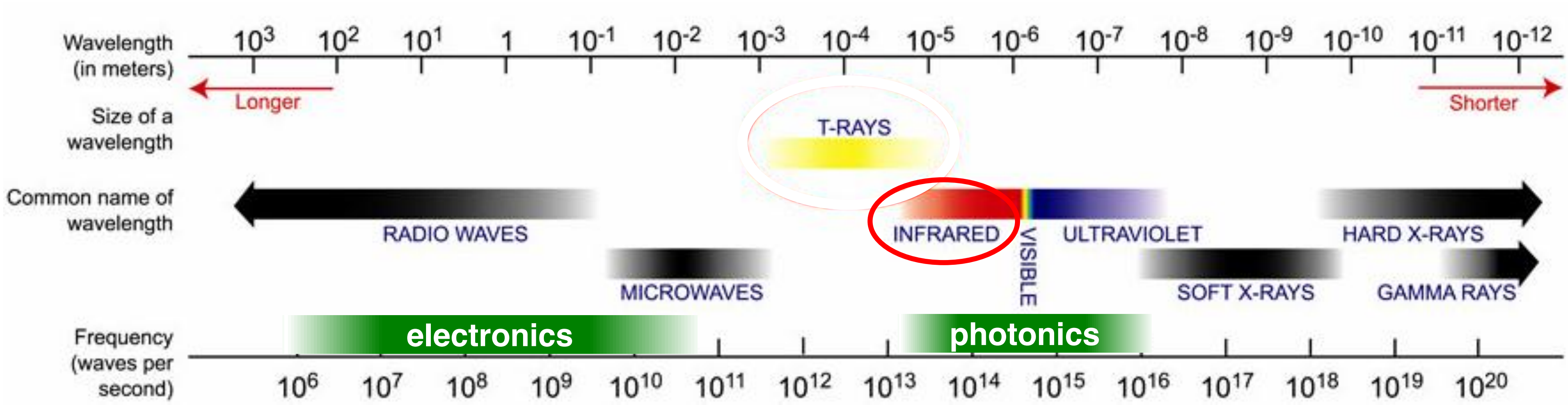


- More applications of optical antennas

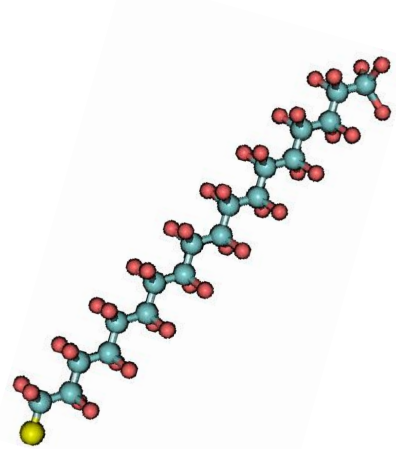


Infrared spectroscopy

Resonant antennas for enhanced signal of molecular vibrations



Molecular fingerprints



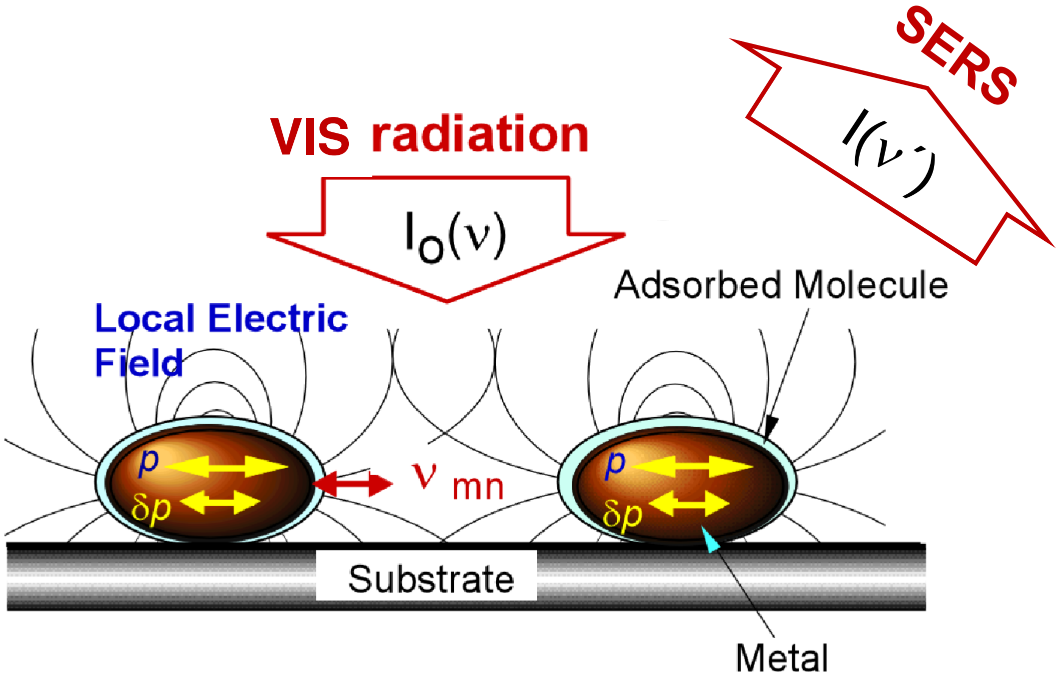
Raman spectroscopy

IR absorption spectroscopy

Surface-Enhanced Raman Scattering (SERS)

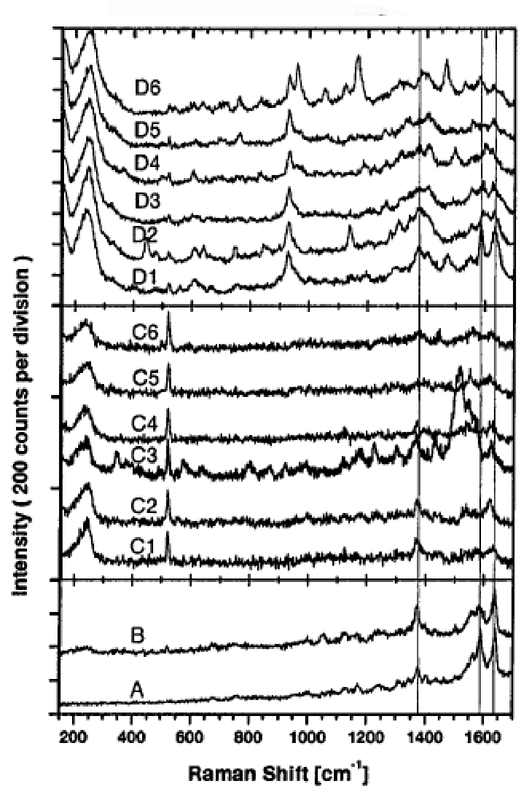
Resonant antennas for enhanced signal of molecular vibrations

Concept



Molecular fingerprints

Identifying molecular vibrations for selective detection of especies in small volumes



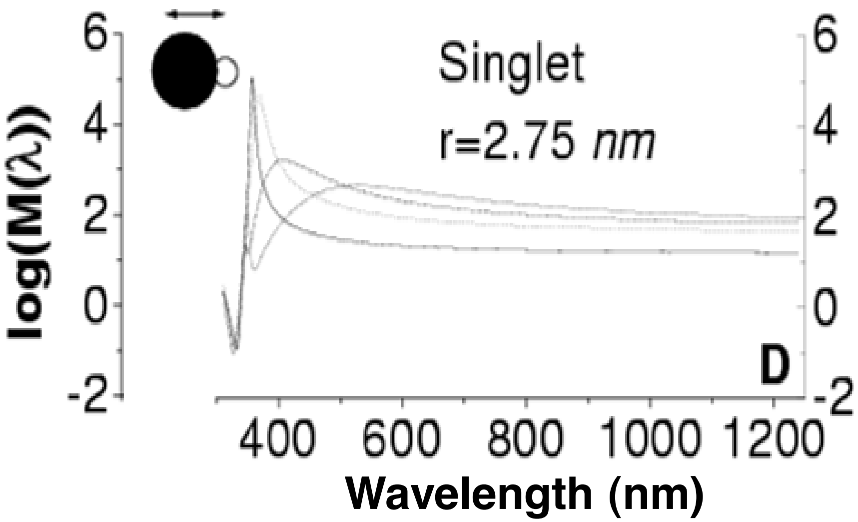
Surface Enhanced Raman Scattering, SERS

Electromagnetic effect

$$M_i^{EM} = \left| E^L(\omega_l) / E^I(\omega_l) \right|^2 \cdot \left| E^L(\omega_l - \omega_v) / E^I(\omega_l - \omega_v) \right|^2$$

If $\omega_v << \omega_I$

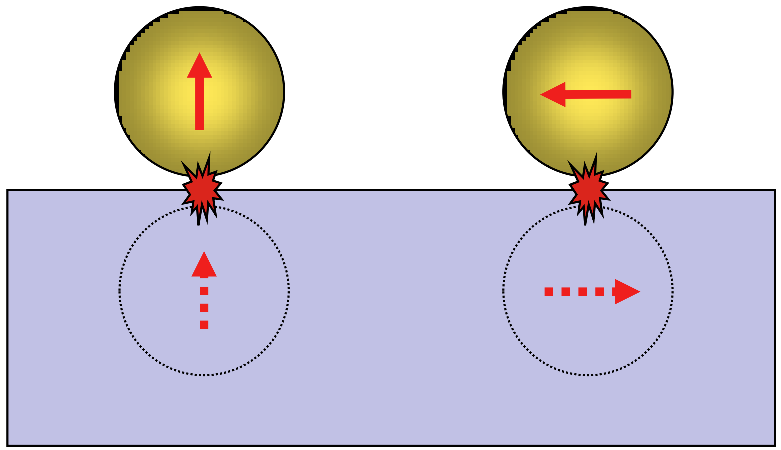
$$M_i^{EM} = \left| E^L(\omega_l) / E^I(\omega_l) \right|^4$$



H. Xu, J. Aizpurua, M. Käll and P. Apell, Phys. Rev. E. **62**, 4318 (2000)

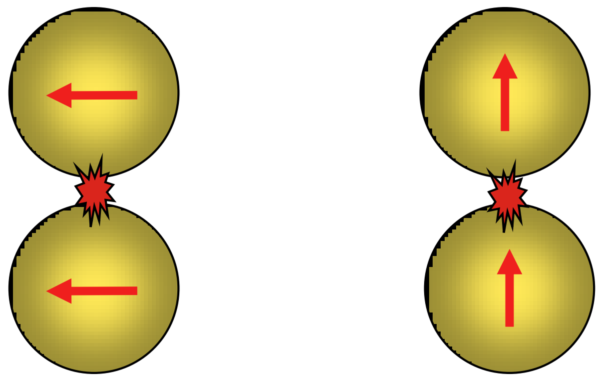
Near-field coupling – simple systems

Sphere - plane



dipole – mirror dipole near-field interaction

Sphere - sphere



dipole – dipole near-field interaction

⟶ High field enhancement in the gap due to resonant near-field coupling

⟶
- local light sources
- enhanced Raman signals (detection of single molecule Raman signals)
- nonlinear effects

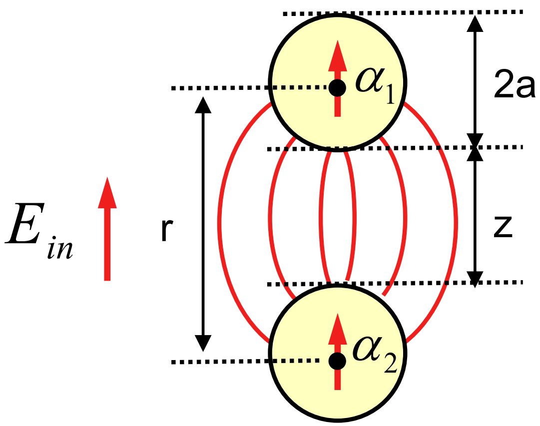
Dipolar sphere-sphere near-field interaction

Polarizability of spheres: $\alpha_i = 4\pi a_i^3 \dfrac{\varepsilon_i - 1}{\varepsilon_i + 2}$

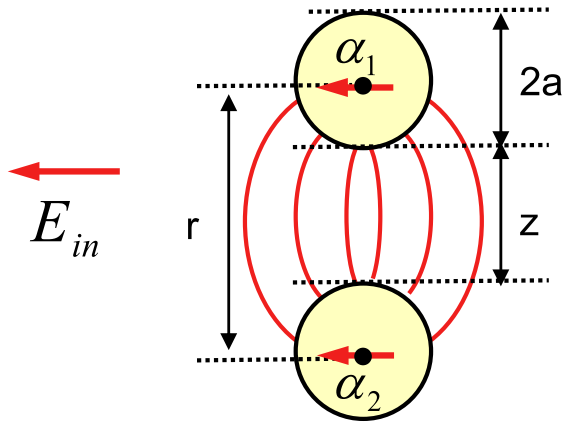
Scattered field:

$$E_{sca} \propto \alpha_{eff} E_{in}$$

Effective polarizability of interacting dipoles (dipole approximation):



$$\alpha_{eff} = \frac{\alpha_1 + \alpha_2 + \dfrac{\alpha_1\alpha_2}{\pi r^3}}{1 - \dfrac{\alpha_1\alpha_2}{4\pi^2 r^6}}$$

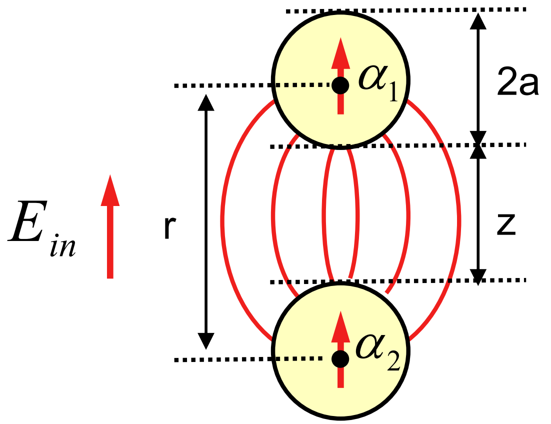


$$\alpha_{eff} = \frac{\alpha_1 + \alpha_2 - \dfrac{\alpha_1\alpha_2}{2\pi r^3}}{1 - \dfrac{\alpha_1\alpha_2}{16\pi^2 r^6}}$$

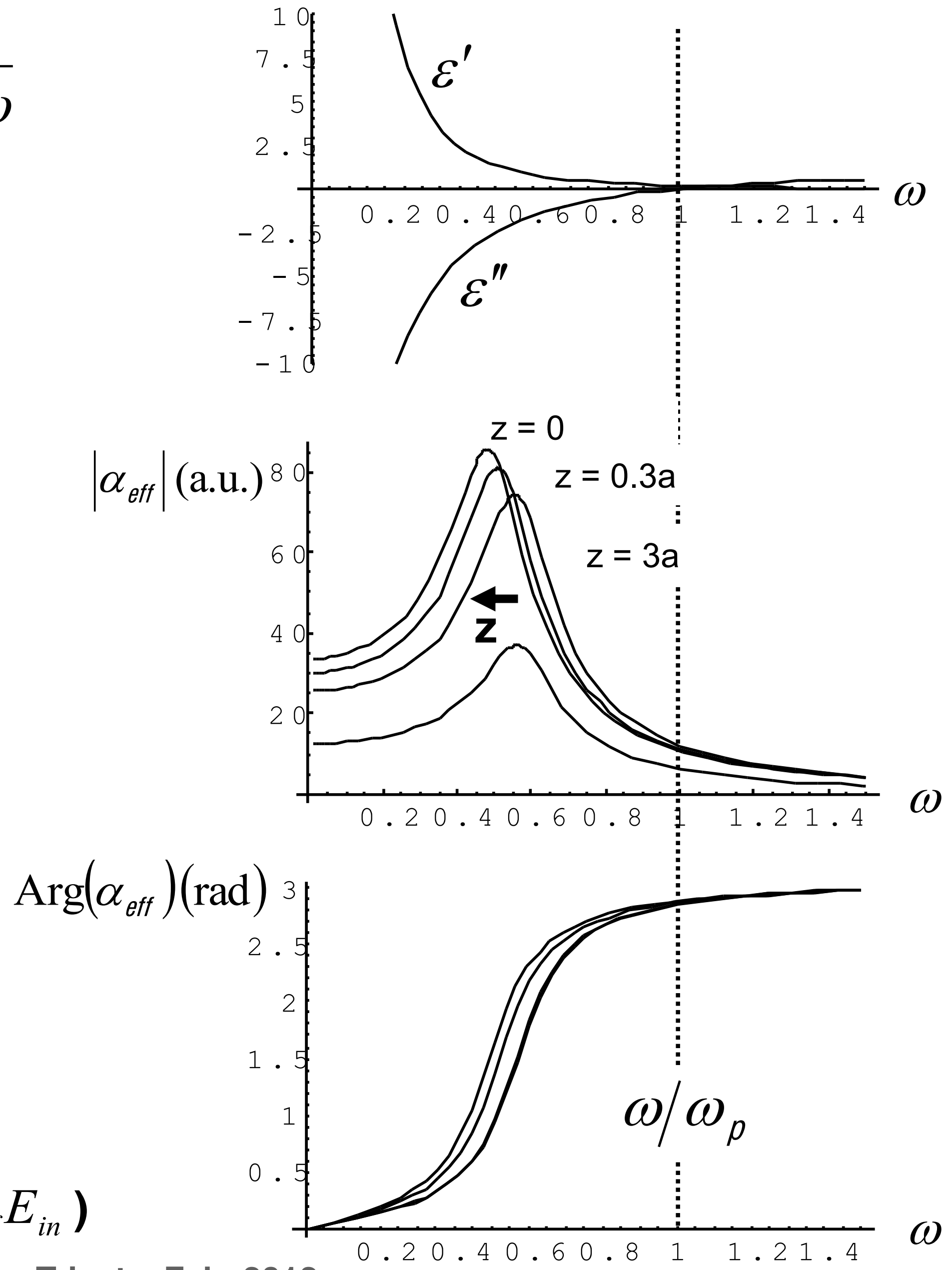
Resonance shift effects – two resonant spheres

2 metal spheres: $\varepsilon_1 = \varepsilon_2 = 1 - \dfrac{\omega_p^2}{\omega^2 + i\gamma\omega}$
(drude term)

$\gamma = 0.2$



$$\alpha_{eff} = \frac{\alpha_1 + \alpha_2 + \dfrac{\alpha_1\alpha_2}{\pi r^3}}{1 - \dfrac{\alpha_1\alpha_2}{4\pi^2 r^6}}$$



→ dipolar approximation predicts

- **resonance shifts**
- **field enhancement** ($E_{sca} \propto \alpha_{eff} E_{in}$)

Two near-field interacting gold discs I

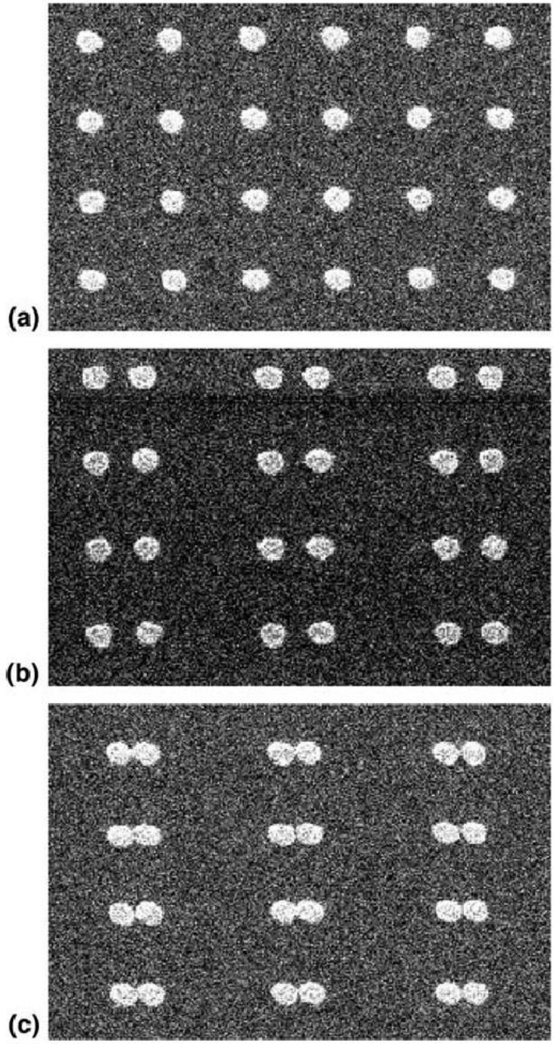


Fig. 1. SEM images of particle pair samples with varying interparticle distance (center-to-center) of (a) 450 nm, (b) 300 nm and (c) 150 nm. The particle diameter is 150 nm, the particle height is 17 nm.

W. Rechenberger et.al., Opt. Commun. 220, 137 (2003)

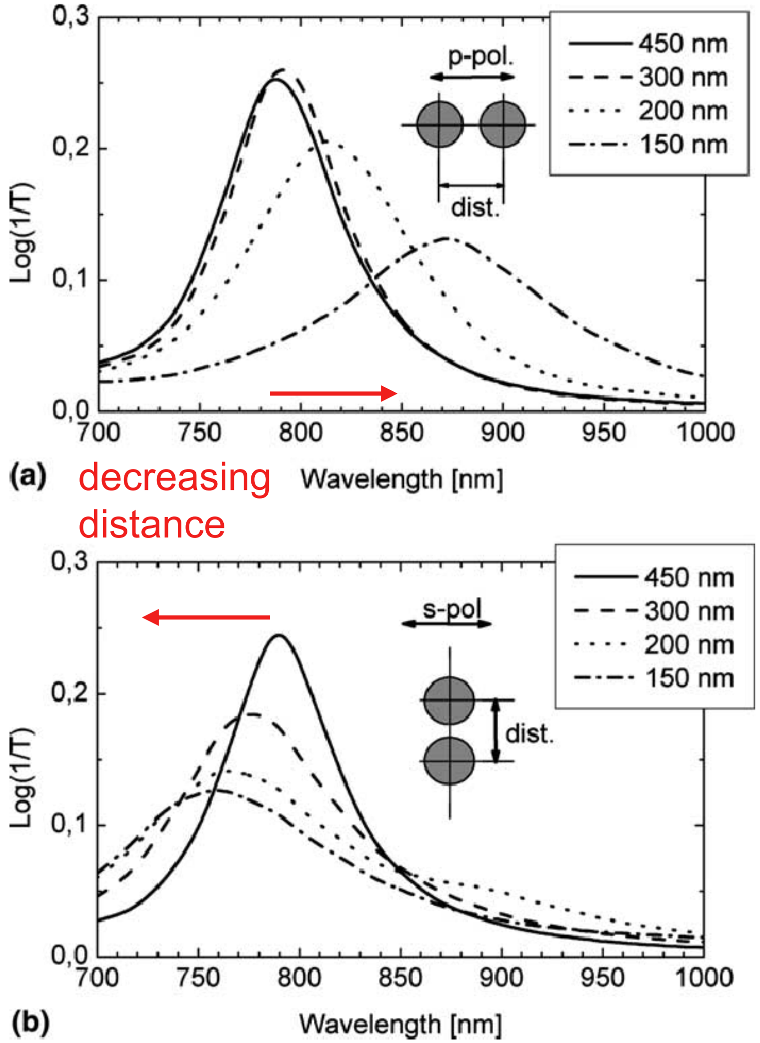
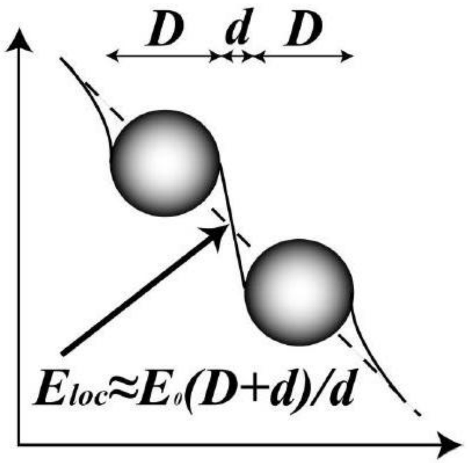
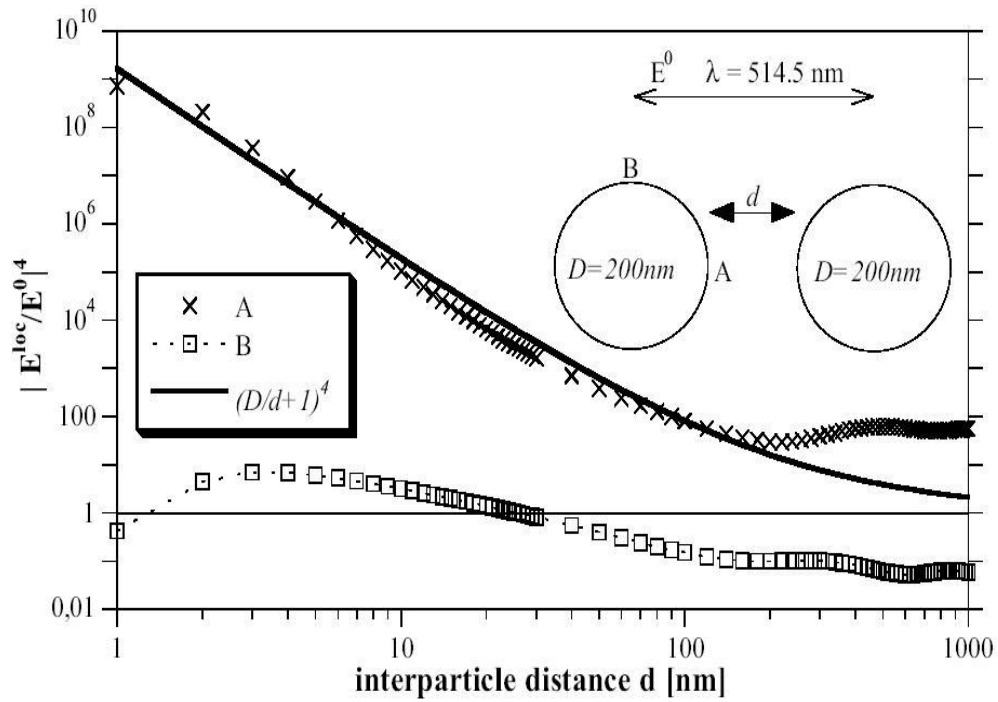


Fig. 2. Extinction (=log(1/Transmission)) spectra of a 2D array of the Au nanoparticle pairs with the interparticle center-to-center distances as the parameter. The orthogonal particle separation is kept constant, as can be seen in Fig. 1. The polarization direction of the exciting light is (a) parallel to the long particle pair axis and (b) orthogonal to it.

Field-enhancement: geometrical squeezing



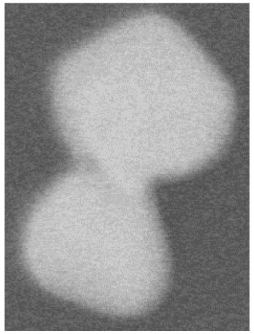


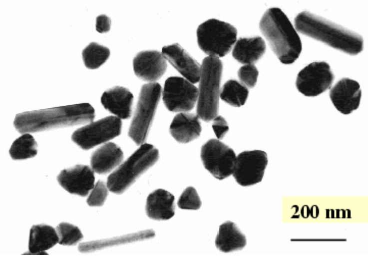
$$E_{loc} = E_0(D + d)/d$$

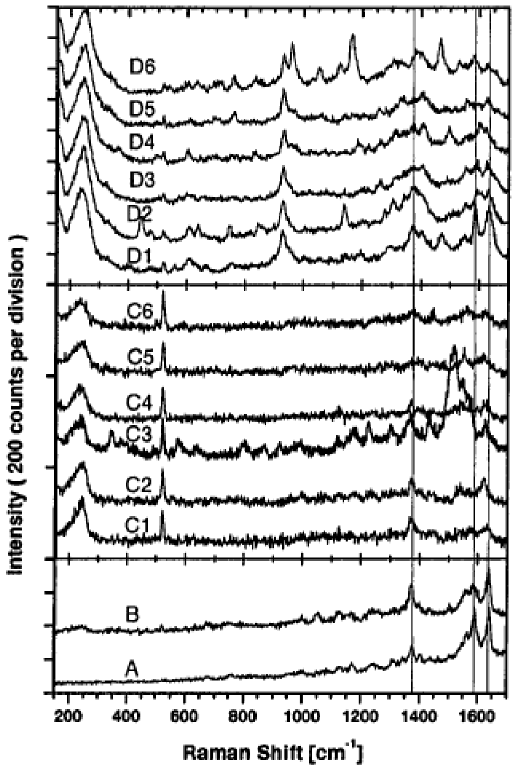
$$M = (\frac{D}{d} + 1)^4$$

Dimers assisting in spectroscopy: SERS

Xu et al. Phys Rev. Lett. (1999)







Xu, Aizpurua, Käll and Apell, Phys. Rev. E. **62**, 4318 (2000)

Hot sites

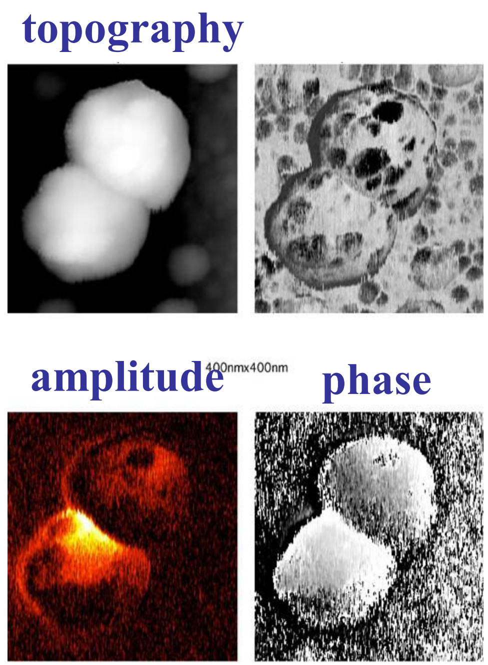
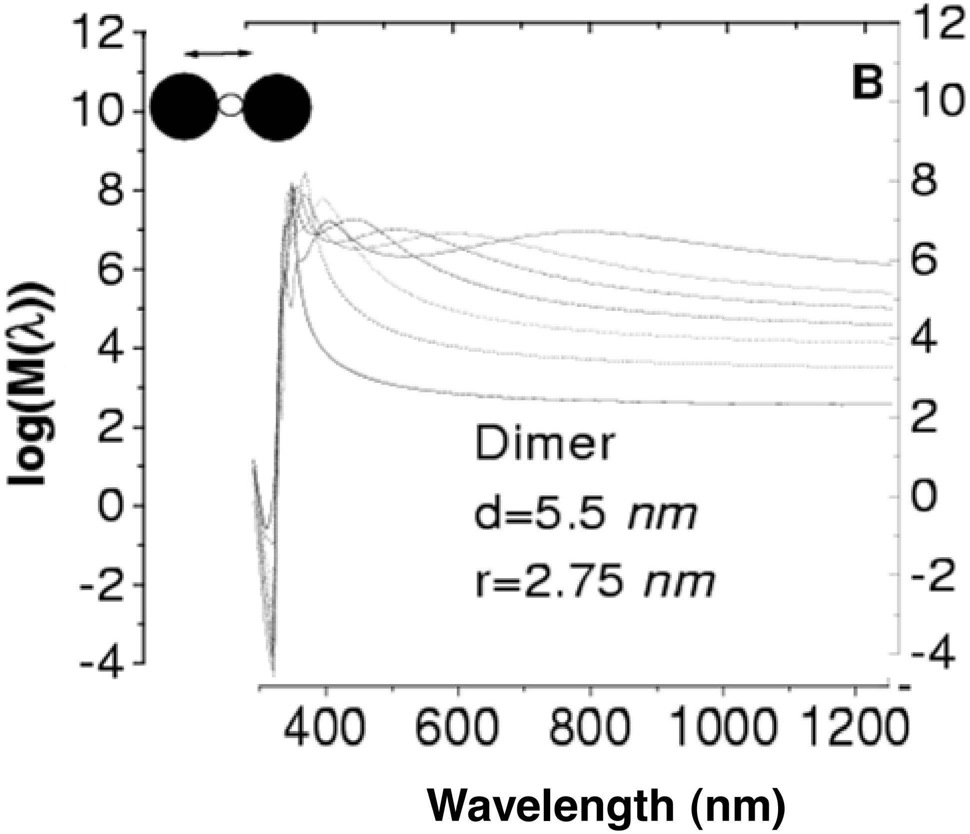


Image obtained by R. Hillenbrand, (Max Planck, Munich)

Dimers assisting in spectroscopy: SERS

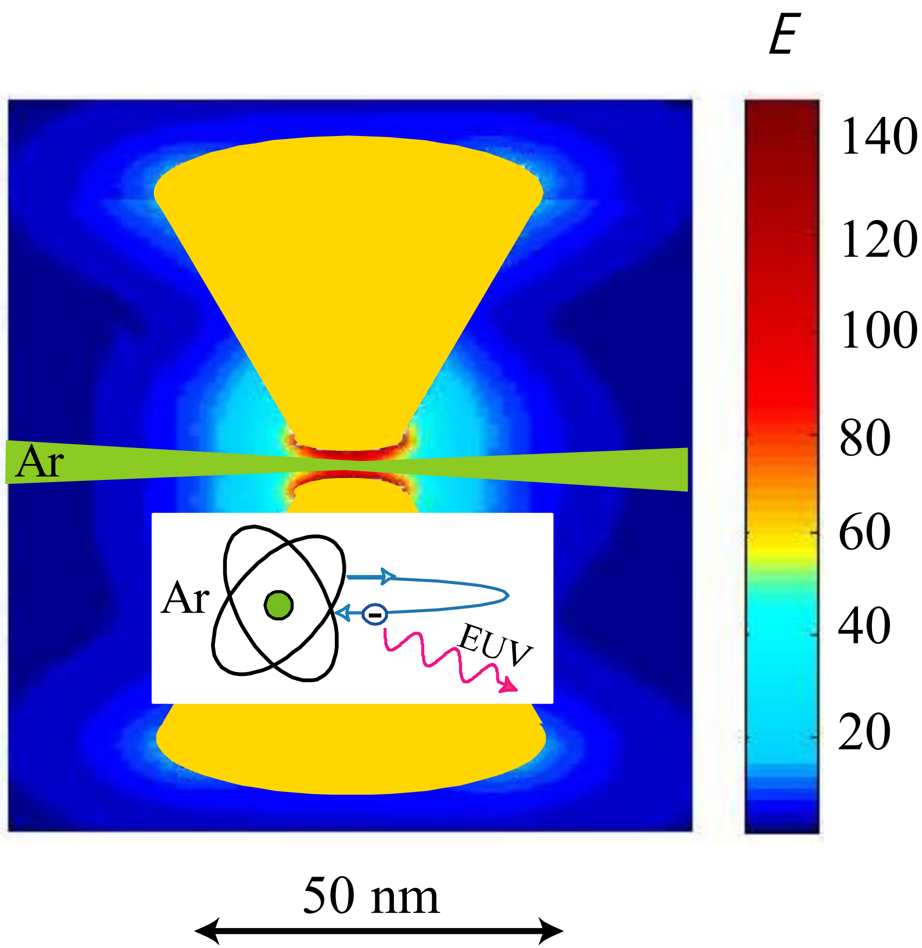
$$M_i^{EM} = \left| E^L(\omega_l) / E^I(\omega_l) \right|^4$$



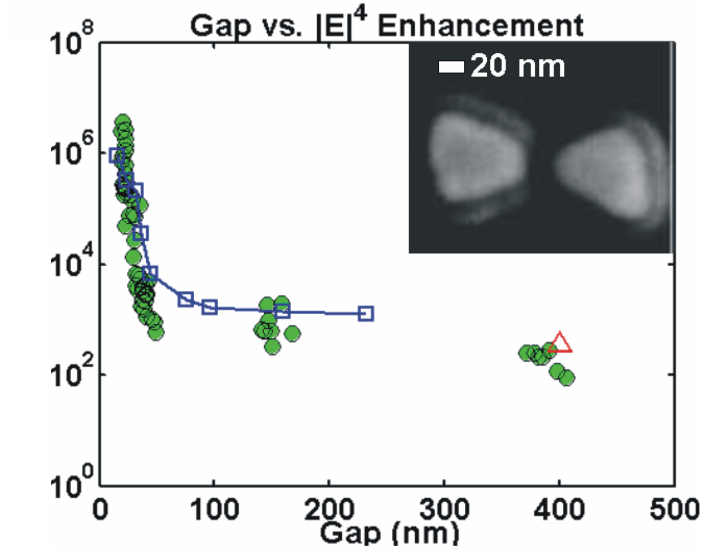
H. Xu, J. Aizpurua, M. Käll and P. Apell, Phys. Rev. E. **62**, 4318 (2000)

Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

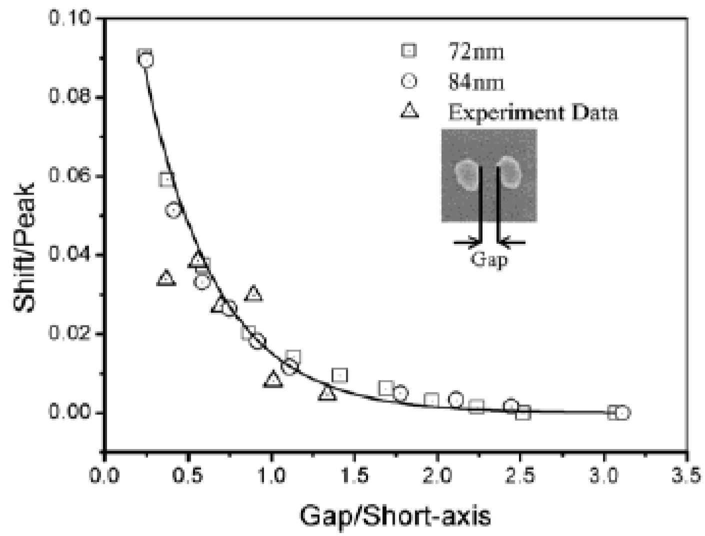
Bowtie nanoantennas



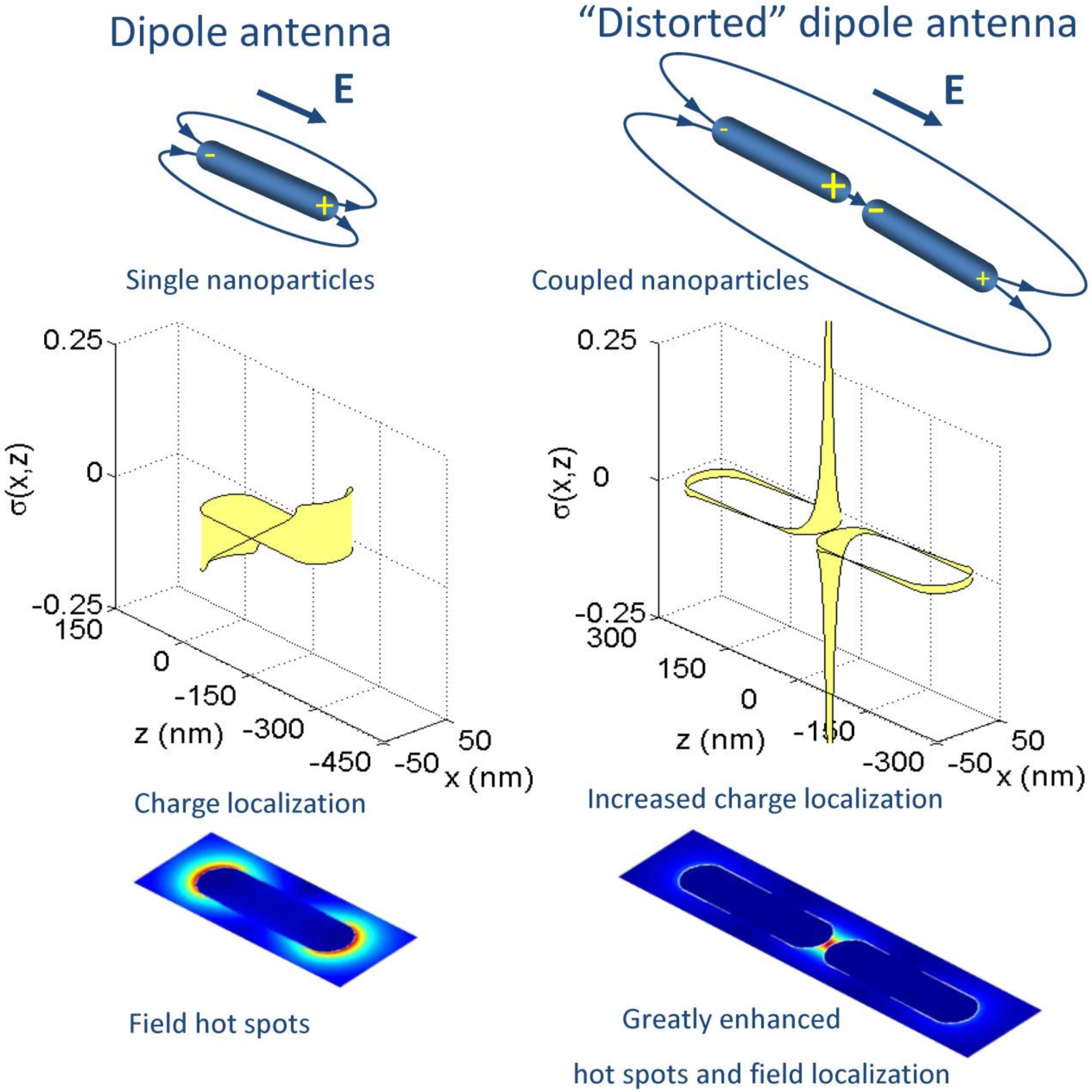
Nature 453, 731 (2008)



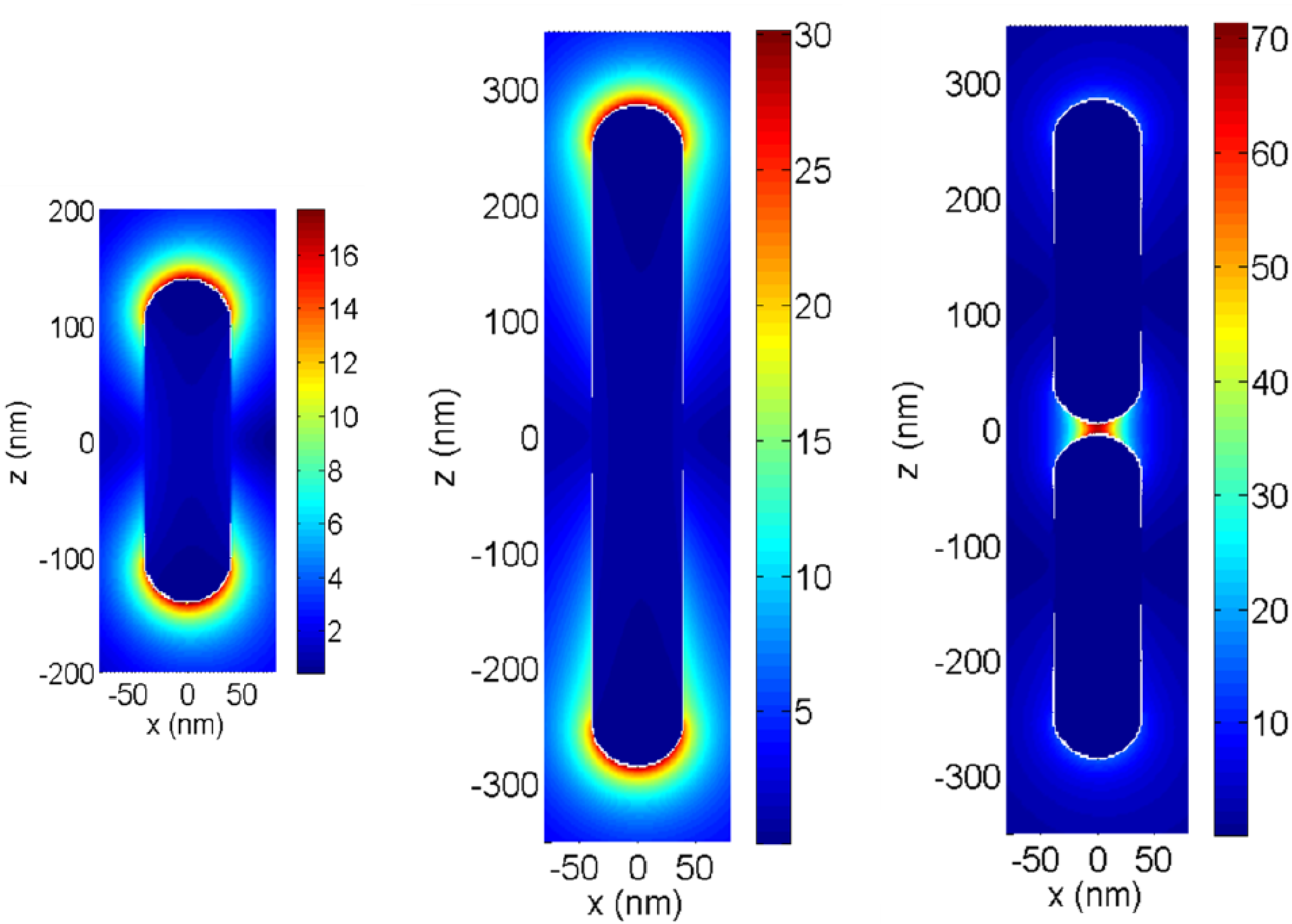
P. J. Schuck, et al, *Phys. Rev. Lett.* **94**, 017402 (2005)



K. H. Su et al, *Nano Lett.* **3**, 1087 (2005)


Dipole antenna
E
Single nanoparticles
0.25
σ(x,z)
0
-0.25
150
0
-150
z (nm)
-300
-450
-50
50
x (nm)
Charge localization
Field hot spots
"Distorted" dipole antenna
E
Coupled nanoparticles
0.25
σ(x,z)
0
-0.25
300
150
0
z (nm)
-150
-300
-50
50
x (nm)
Increased charge localization
Greatly enhanced
hot spots and field localization

Gap antenna: localization and field-enhancement: hot-sites



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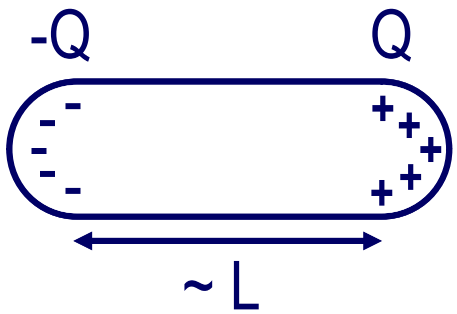
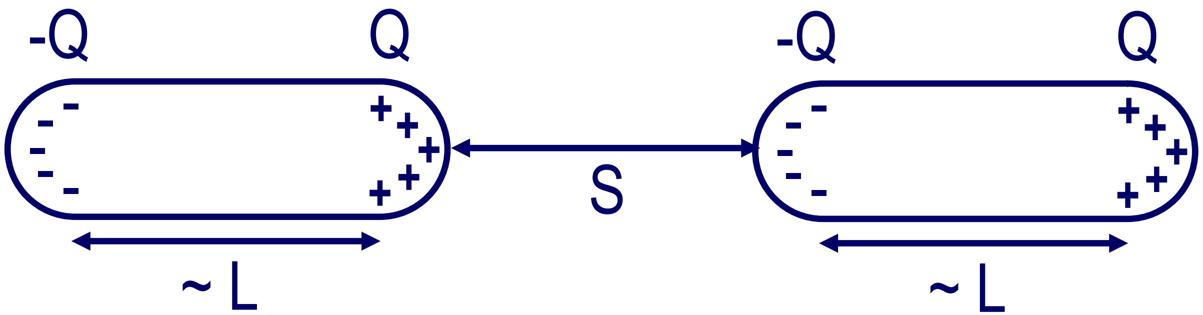
Distorted dipole

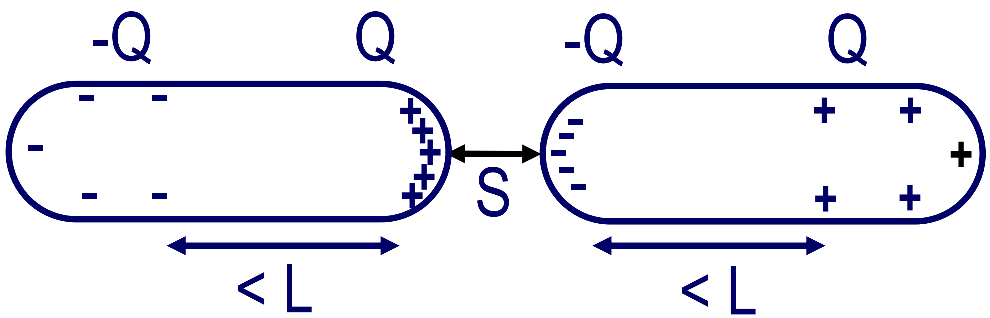
Isolated rod: dipole



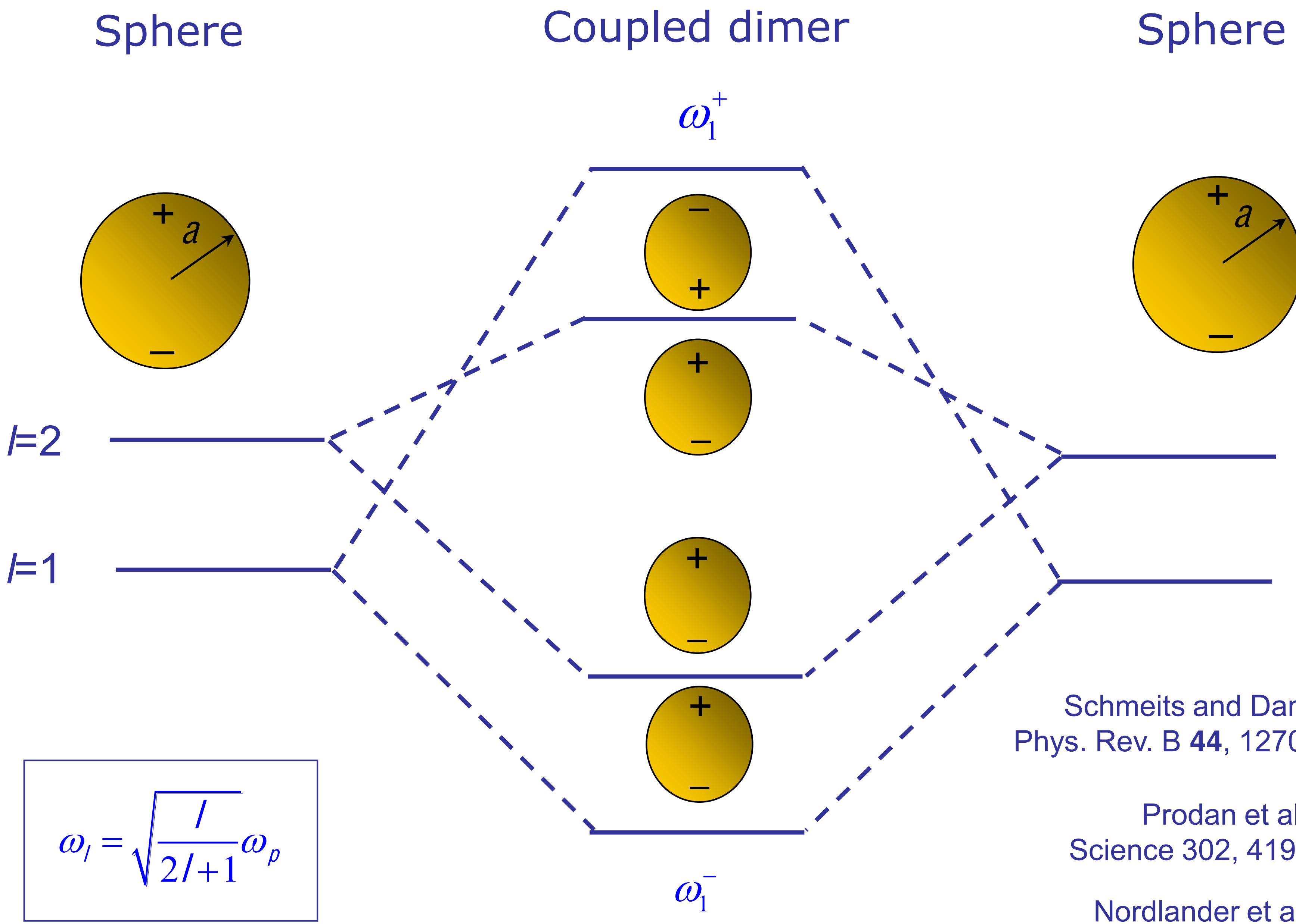
Weak coupling:
two dipoles



Strong coupling:
distorted dipoles



Plasmon hybridization



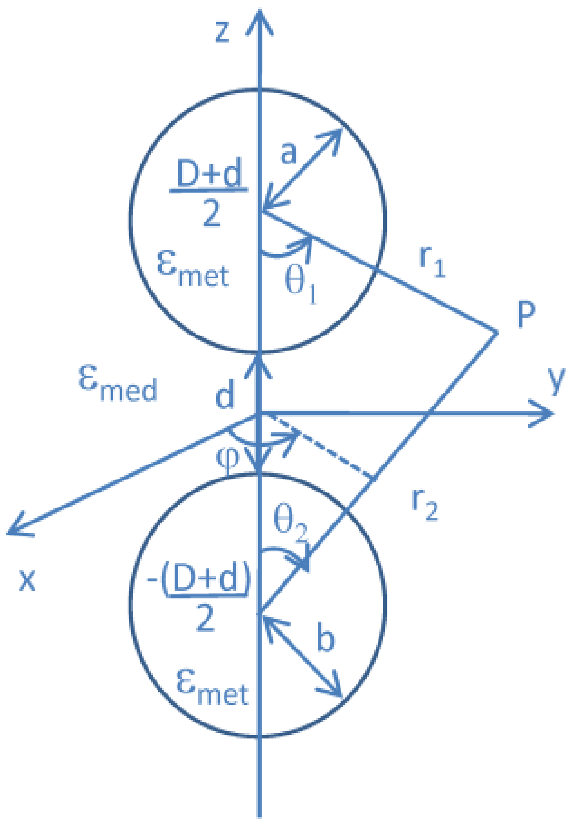
$$\omega_l = \sqrt{\frac{l}{2l+1}}\,\omega_p$$

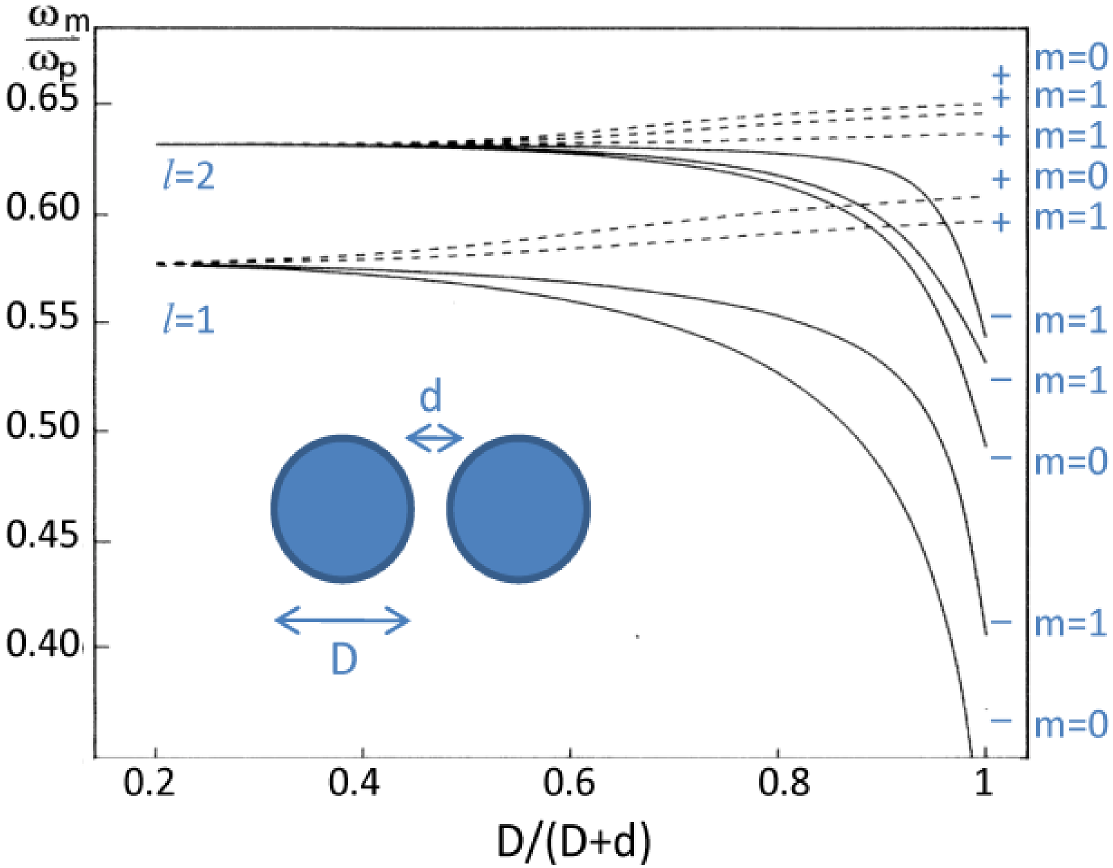
Schmeits and Dambly,
Phys. Rev. B **44**, 12706 (1991)

Prodan et al,
Science 302, 419 (2003)

Nordlander et al,
Nanoletters **4**, 899 (2004)

Coupled modes in a metallic dimer





$$\Psi^{(1)}(r,\theta,\varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=+l} \left(\frac{r_1}{a}\right)^l A_{lm}\, Y_{lm}(\theta_1,\varphi)\, e^{im\varphi} \quad for\ r_1 < a,$$

$$\Psi^{(2)}(r,\theta,\varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=+l} \left(\frac{r_2}{b}\right)^l D_{lm}\, Y_{lm}(\theta_2,\varphi)\, e^{im\varphi} \quad for\ r_2 < b,$$

$$\Psi^{(3)}(r,\theta,\varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=+l} \left[\left(\frac{a}{r_1}\right)^{l+1} B_{lm} Y_{lm}(\theta_1,\varphi) + \left(\frac{b}{r_2}\right)^{l+1} C_{lm}\, Y_{lm}(\theta_2,\varphi)\right] e^{im\varphi}$$

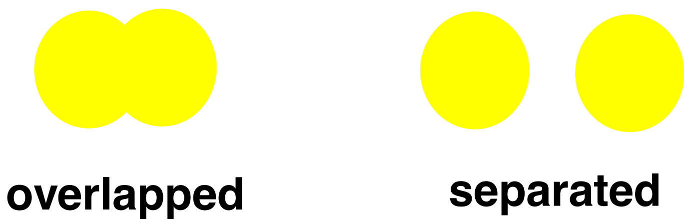
$$\left(\frac{\omega_{m=0;l=1}}{\omega_p}\right)^2_{\pm} = \frac{\left(1 \pm 2\left(\frac{D/2}{D+d}\right)^3\right)}{3}$$

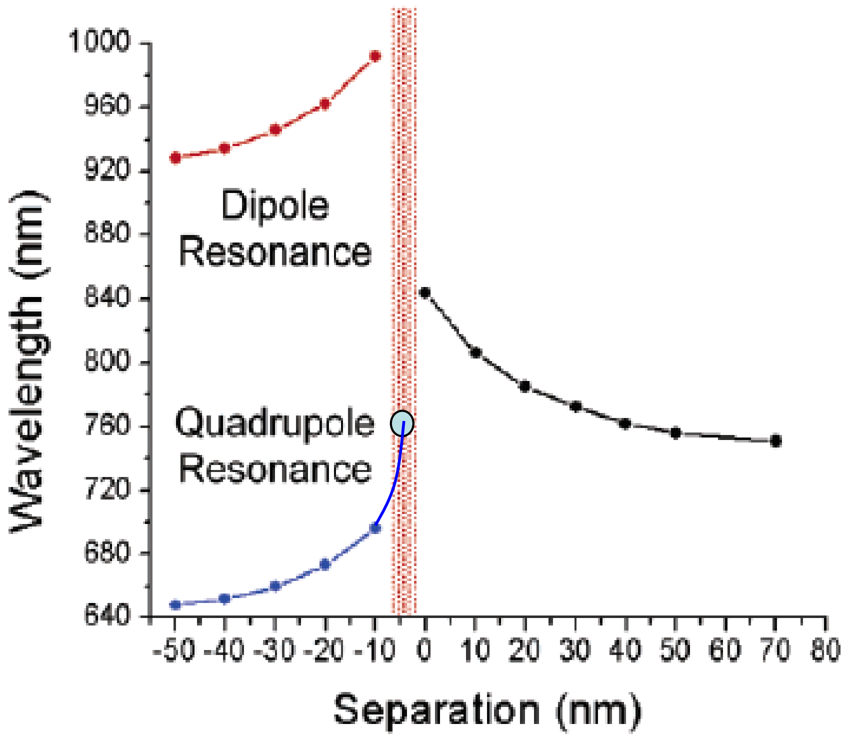
Schmeits and Dambly,
Phys. Rev. B **44**, 12706 (1991)

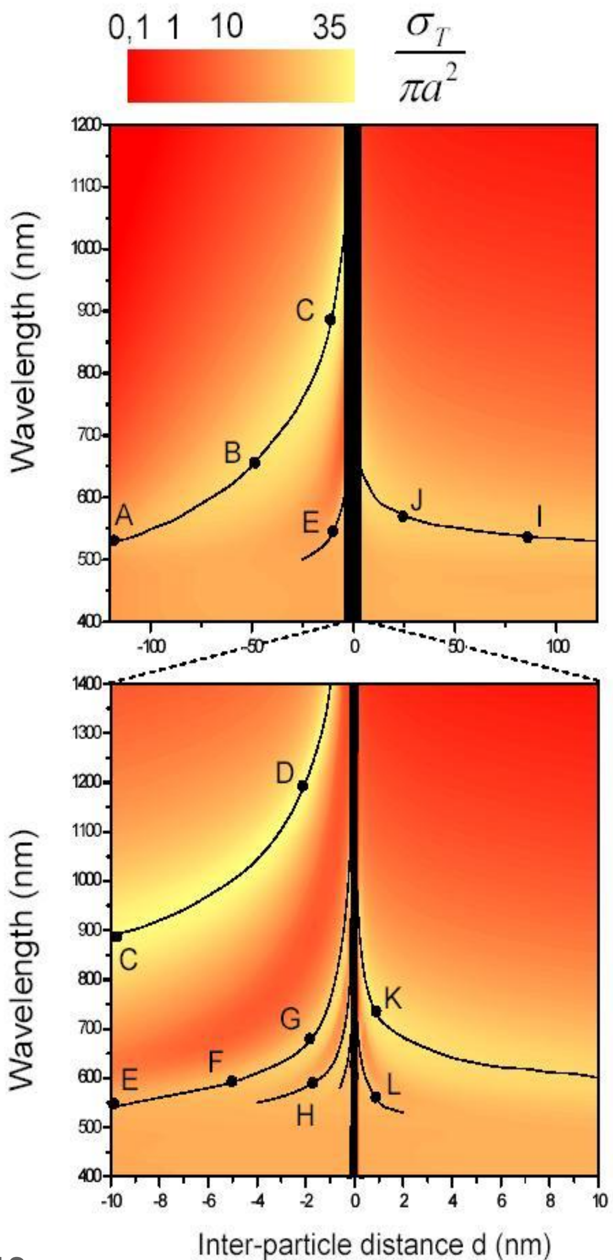
Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

Nanoparticles in the touching limit

Map of the resonances





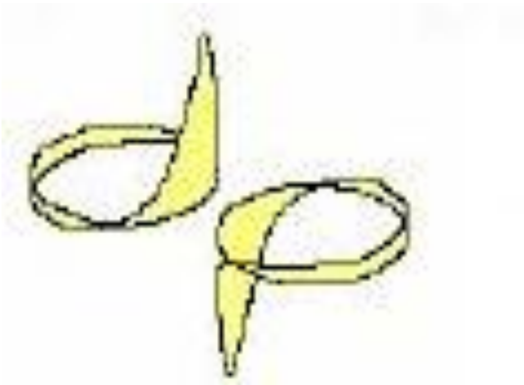


I. Romero, *et al*. Optics Express 14, 9988 (2006)

Charge density modes

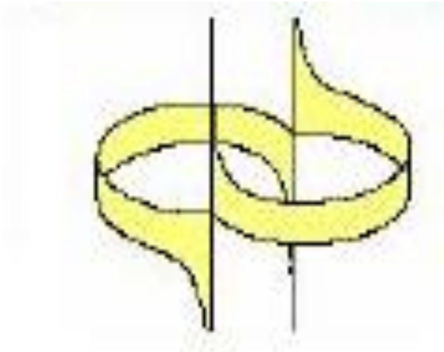
Low frequency modes of non-touching and touching dimers are distinctly different

NOT TOUCHING

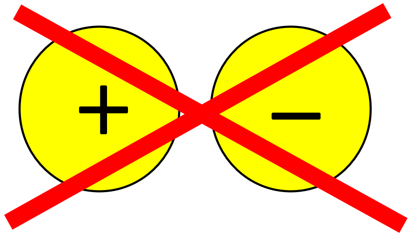


Neutral charge in each particle

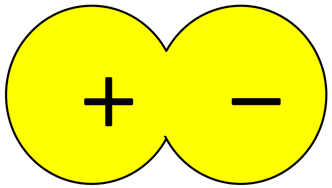
TOUCHING



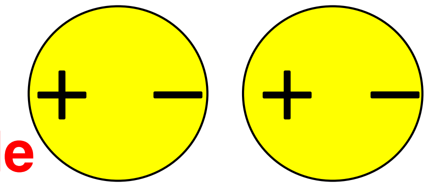
Net electrical charge in each half of the dimer



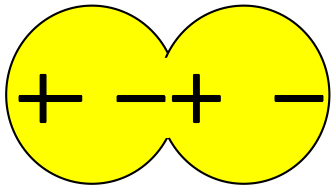
Unphysical mode



1st physical mode



1st physical mode



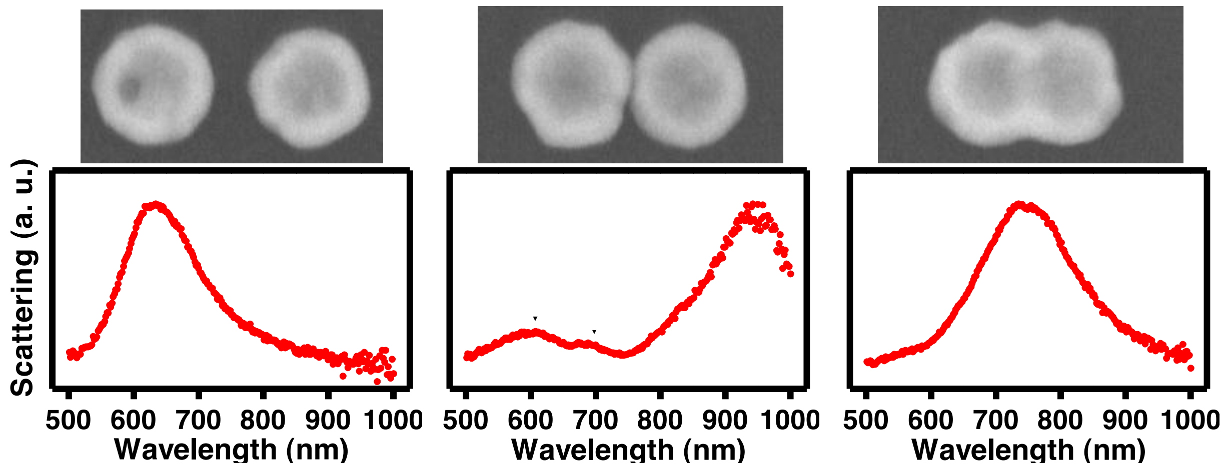
2nd physical mode

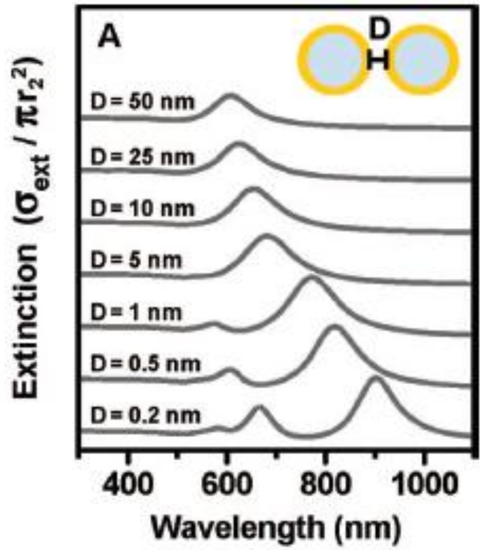
Close Encounters between Two Nanoshells

J. Britt Lassiter,[†,‖] Javier Aizpurua,[⊥] Luis I. Hernandez,[‖] Daniel W. Brandl,[†,‖] Isabel Romero,[⊥] Surbhi Lal,[‡,‖] Jason H. Hafner,[†,§,‖] Peter Nordlander,[†,‡,‖] and Naomi J. Halas*[,‡,§,‖]

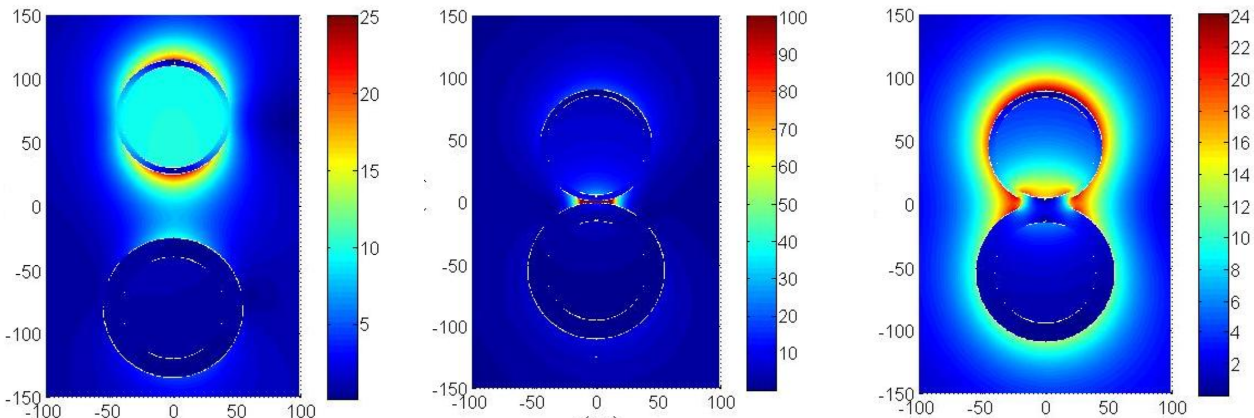
NANO LETTERS

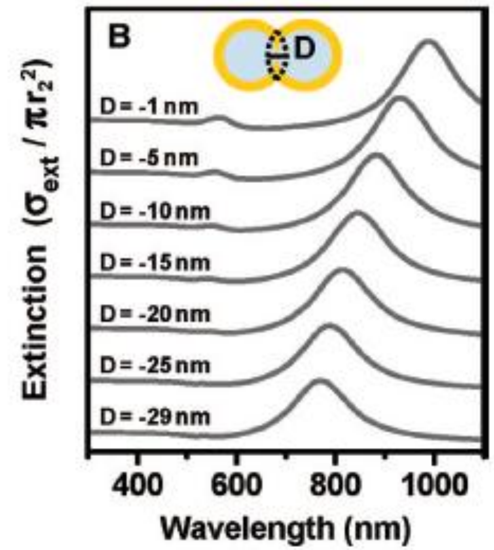
2008
Vol. 8, No. 4
1212-1218





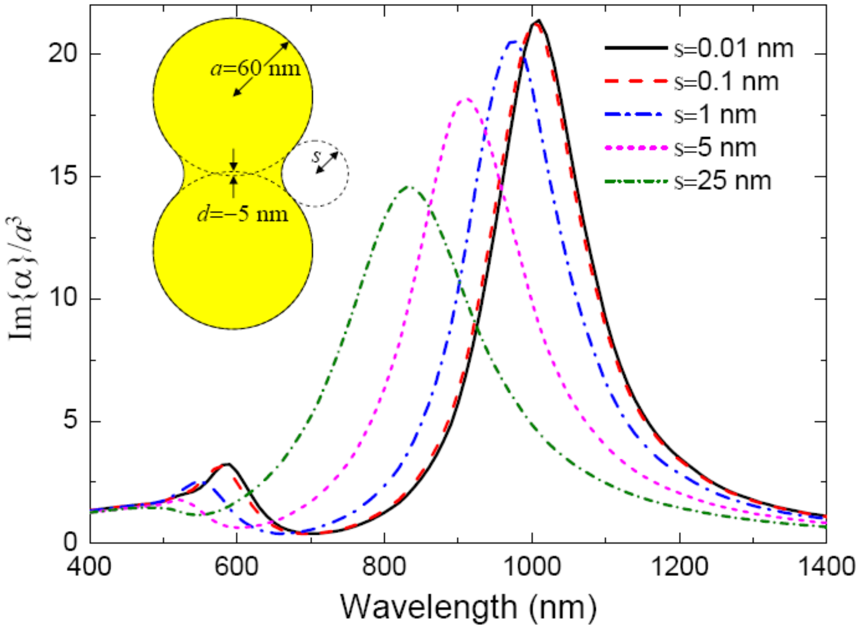
Slightly close: Slight shift | **Close proximity: red shift** | **Overlapped: Blue-shift**



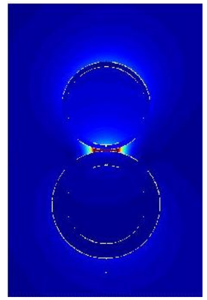


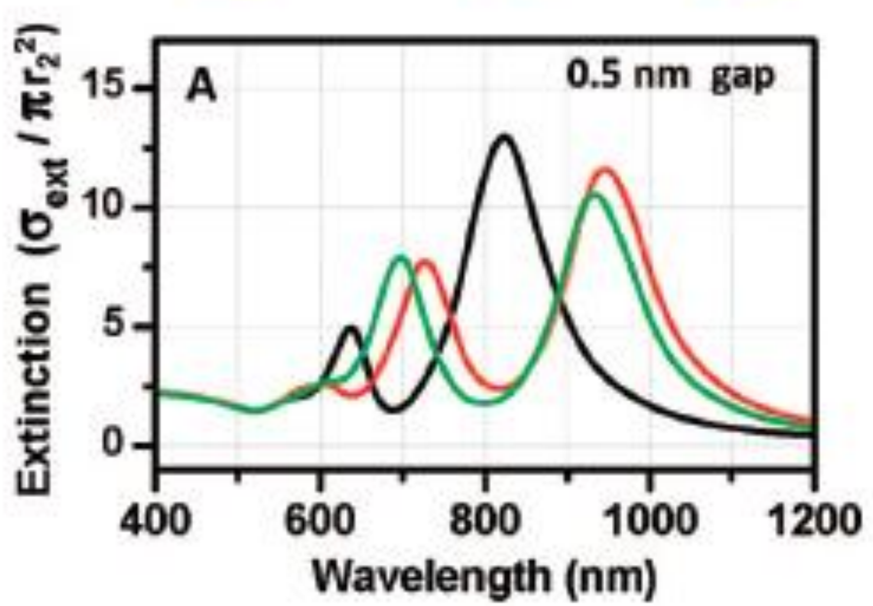
The fine detail of the junction matters!!!

Specially for resonant spectroscopy



I. Romero et al. Optics Express 14, 9988 (2006)

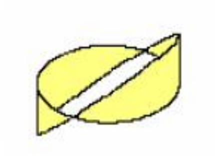


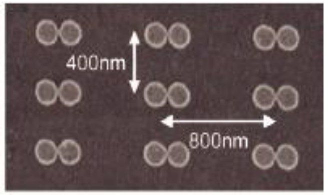


J.B. Lassiter, Nano Letters 8, 1212 (2008)

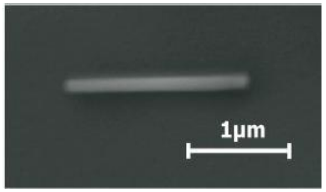
Outline

- Optical antennas: Basics

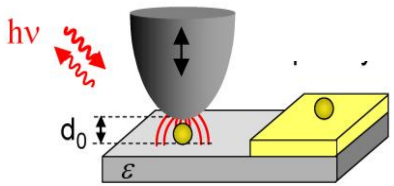




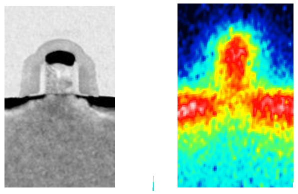
- Playing with antenna modes



- Optical antennas for Enhanced Spectroscopy : SEIRA

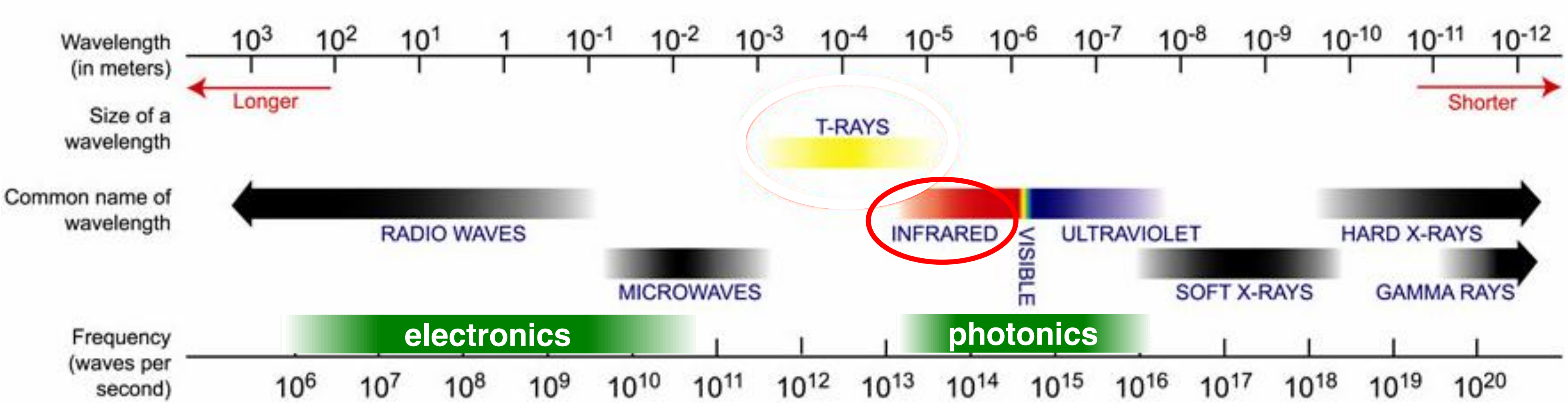


- More applications of optical antennas



Surface-enhanced IR absorption (SEIRA)

Resonant antennas for enhanced signal of molecular vibrations

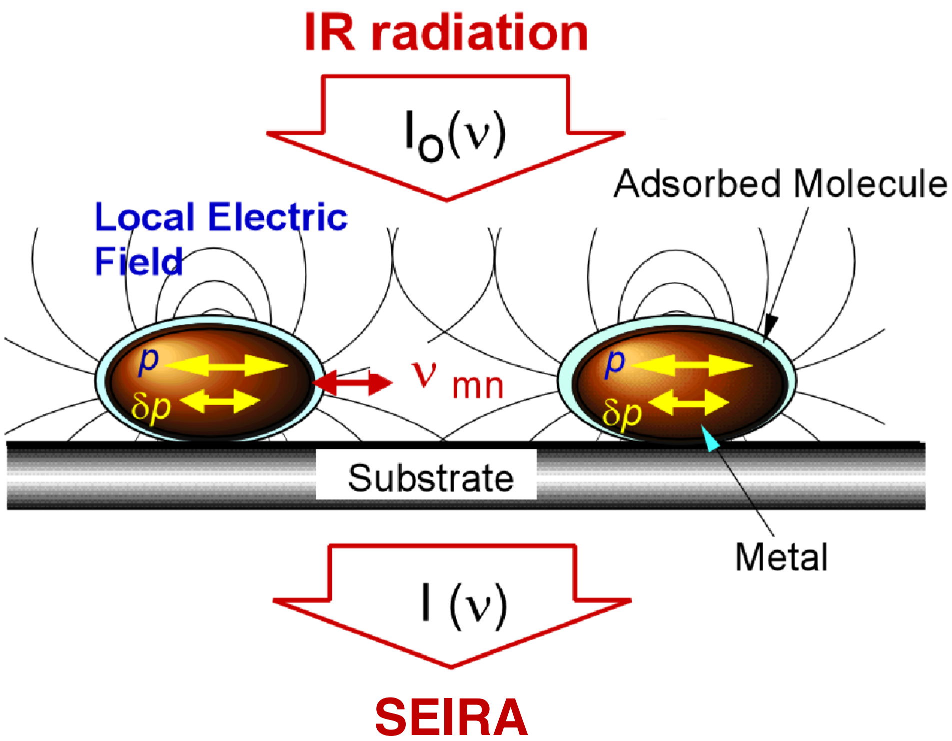


Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

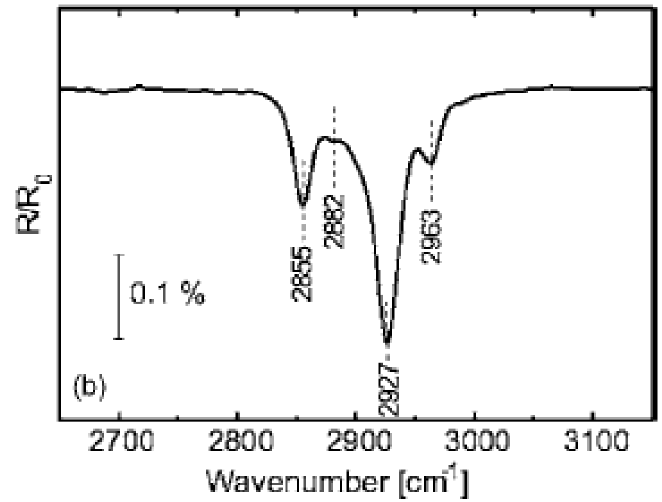
Surface-enhanced IR absorption (SEIRA)

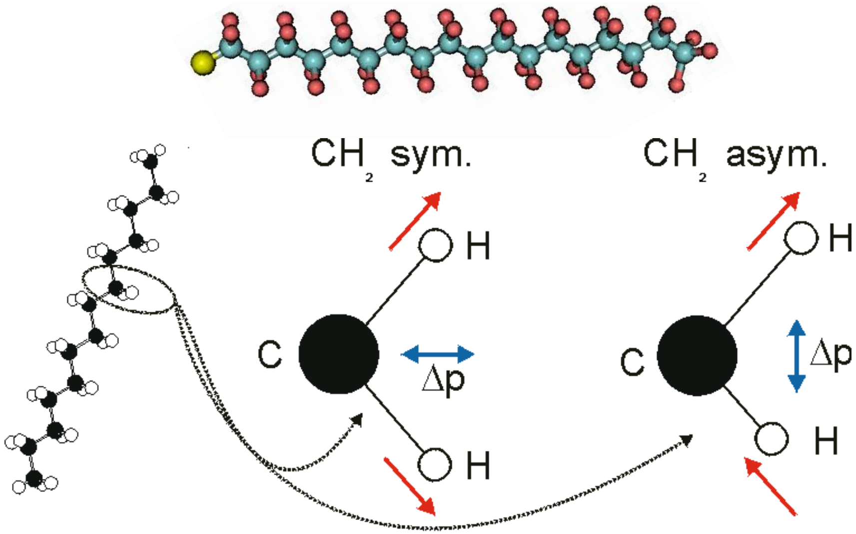
Resonant antennas for enhanced signal of molecular vibrations

Concept

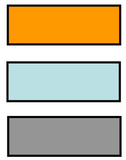


ODT Molecular fingerprints



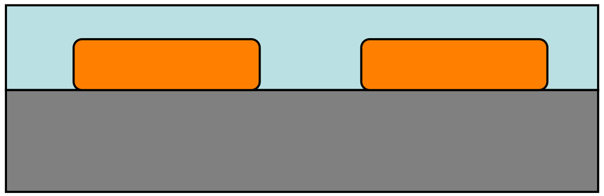


How to bring resonances of nanoscale objects to the mid-infrared ??



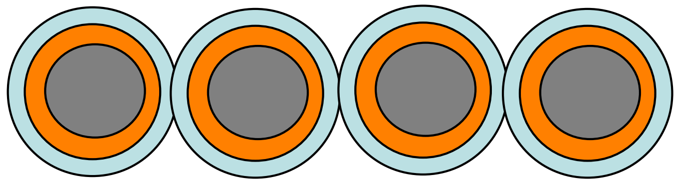
Resonant structure
Layer to be investigated
Non-resonant structure

Resonant triangles (coated)



T.R. Jensen et al., J. Phys. Chem B, 104, 10549 (2000)

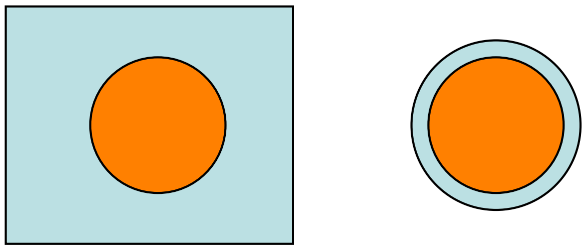
Nanoshell arrays



H. Wang et al., Angew. Chem. 46, 9040 (2007)

Resonant particle

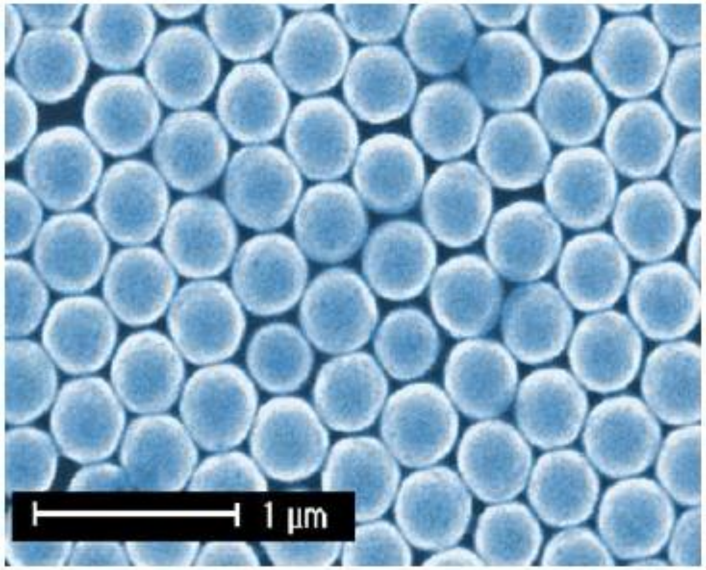
(coated) (embedded)

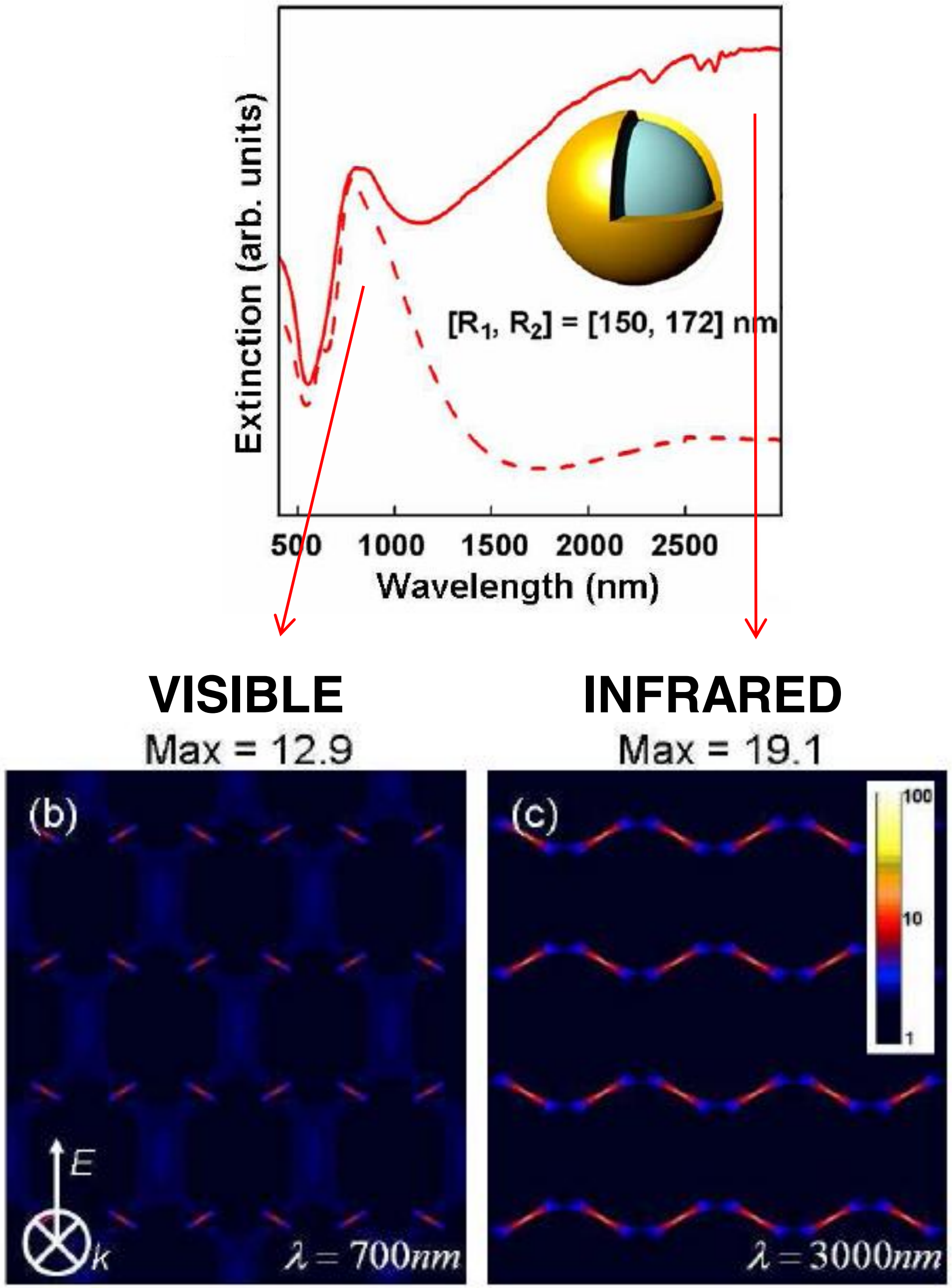


M.S. Anderson, App. Phys. Lett. 83, 2964 (2003)

Nanoshell arrays: Substrates for infrared spectroscopy

Metallic nanoparticle arrays for SERS and SEIRA





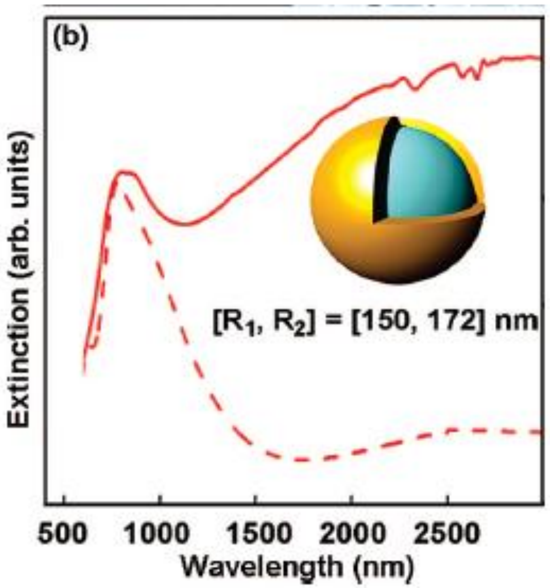
Kundu et al. Angew. Chem. (2007)
Halas group, Rice Univ.

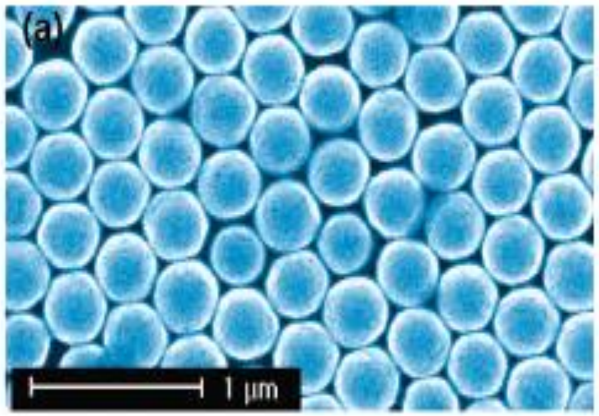
Fei et al. ACS Nano. 2, 707 (2008)
In collaboration with P. Nordlander's group

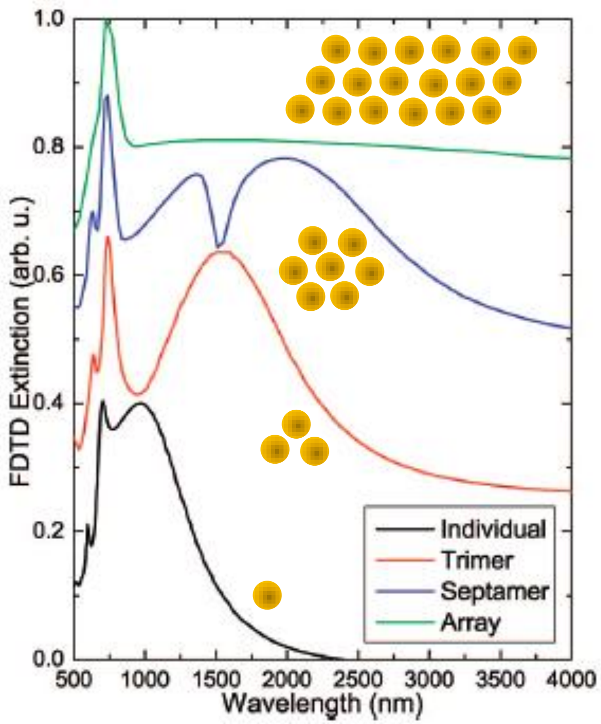
Metallic Nanoparticle Arrays: A Common Substrate for Both Surface-Enhanced Raman Scattering and Surface-Enhanced Infrared Absorption

ACS NANO
2, 707 (2008)

Fei Le,[†] Daniel W. Brandl,[†] Yaroslav A. Urzhumov,[‡] Hui Wang,[§] Janardan Kundu,[§] Naomi J. Halas,[§,⊥]
Javier Aizpurua,[‖] and Peter Nordlander[†,⊥,*]







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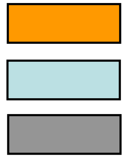
Single antenna for infrared resonant spectroscopy



Resonant structure
Layer to be investigated
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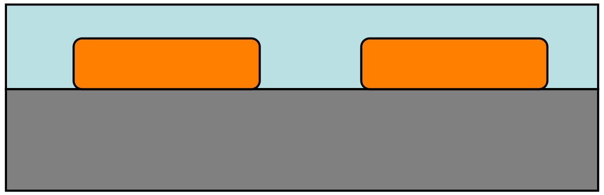
Resonant triangles (coated)



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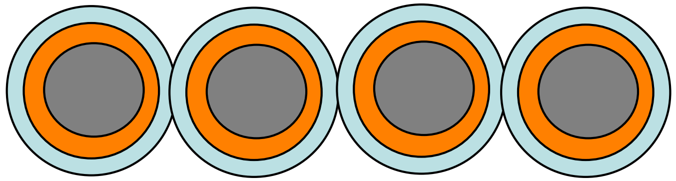
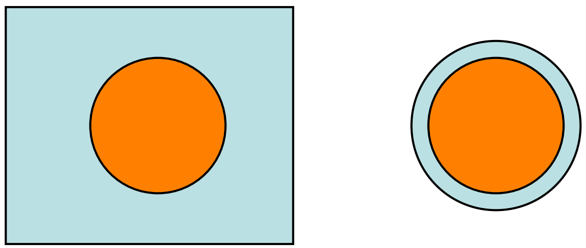
Nanoshell arrays



H. Wang et al., Angew. Chem. 46, 9040 (2007)

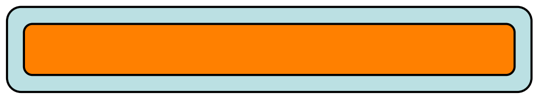
Resonant particle

(coated) (embedded)



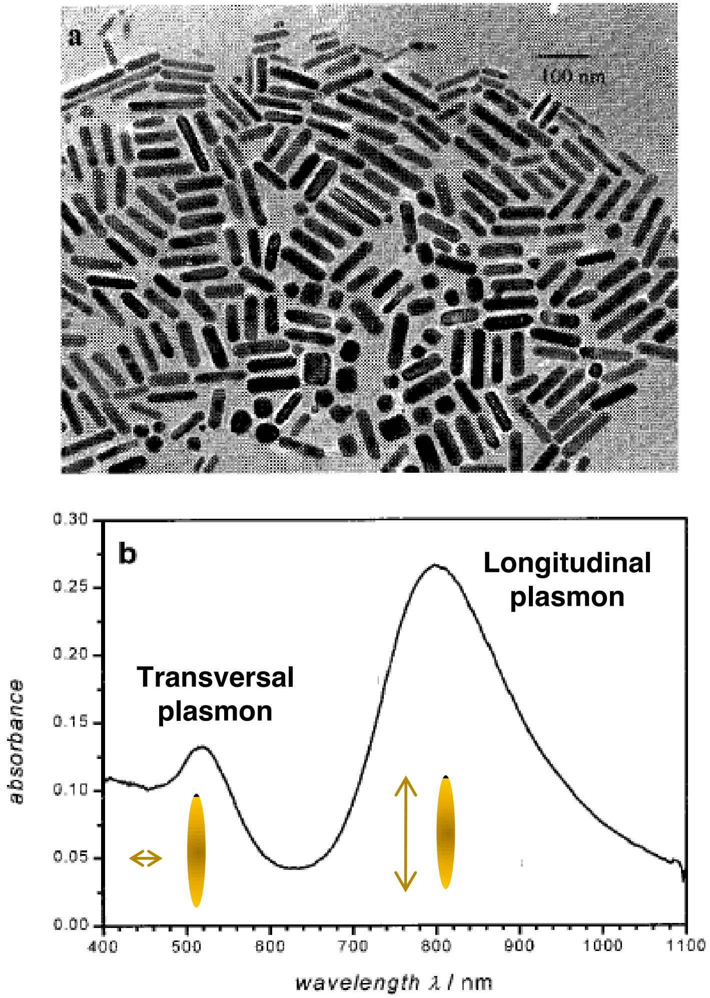
M.S. Anderson, App. Phys. Lett. 83, 2964 (2003)

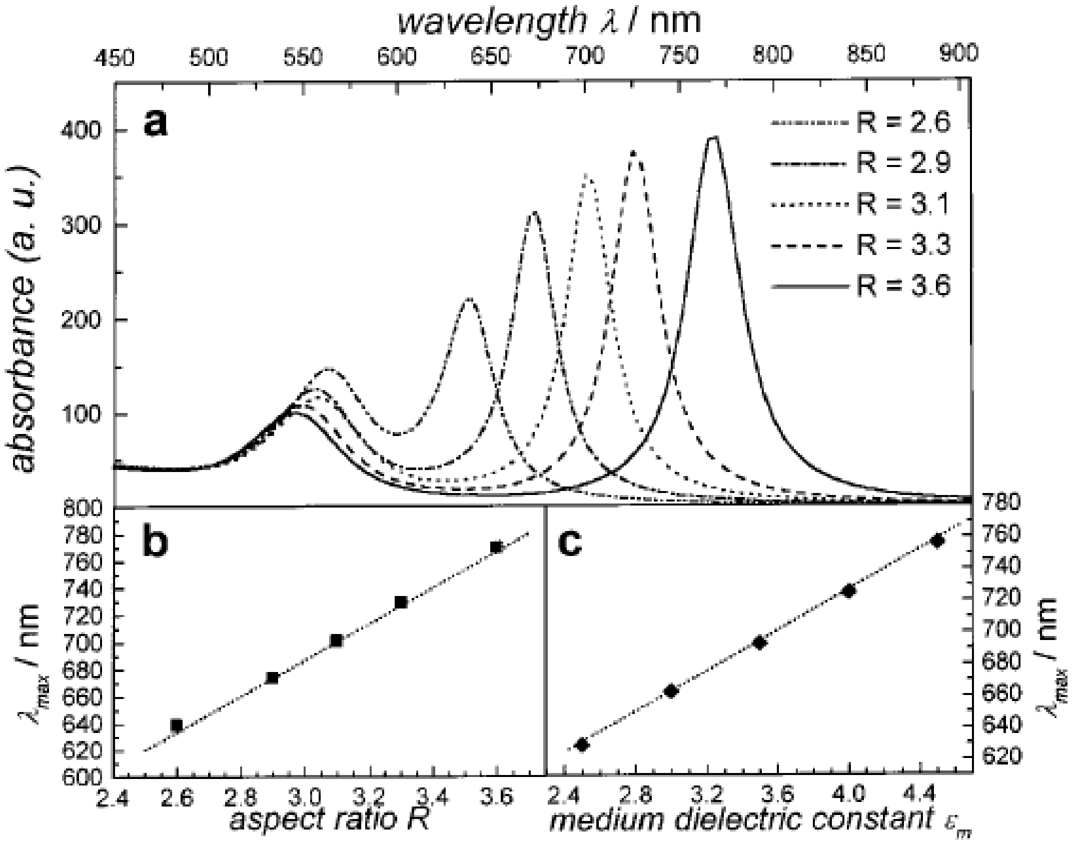
Resonant rod (coated)



F. Neubrech et al.,
Phys. Rev. Lett. 101, 157403 (2008)

Basics of nanorods





L=λ/m ?

S. Link and M.A. El-Sayed. J. Phys. Chem. B 103,8410 (1999).

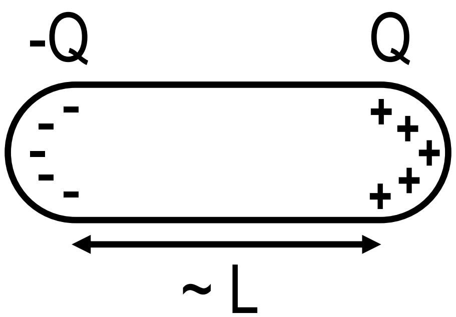
Calculation of gold antenna modes

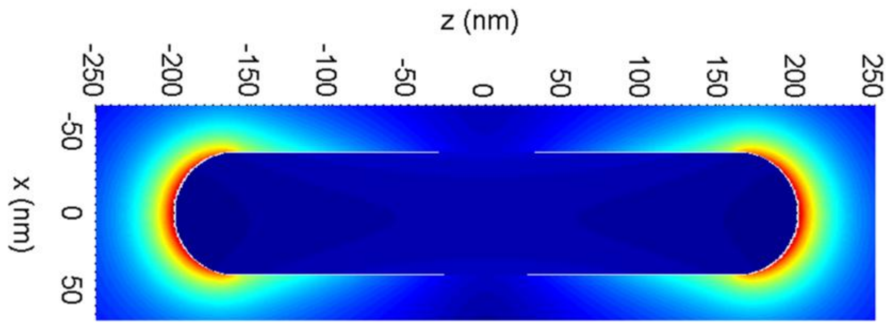
Antenna modes:

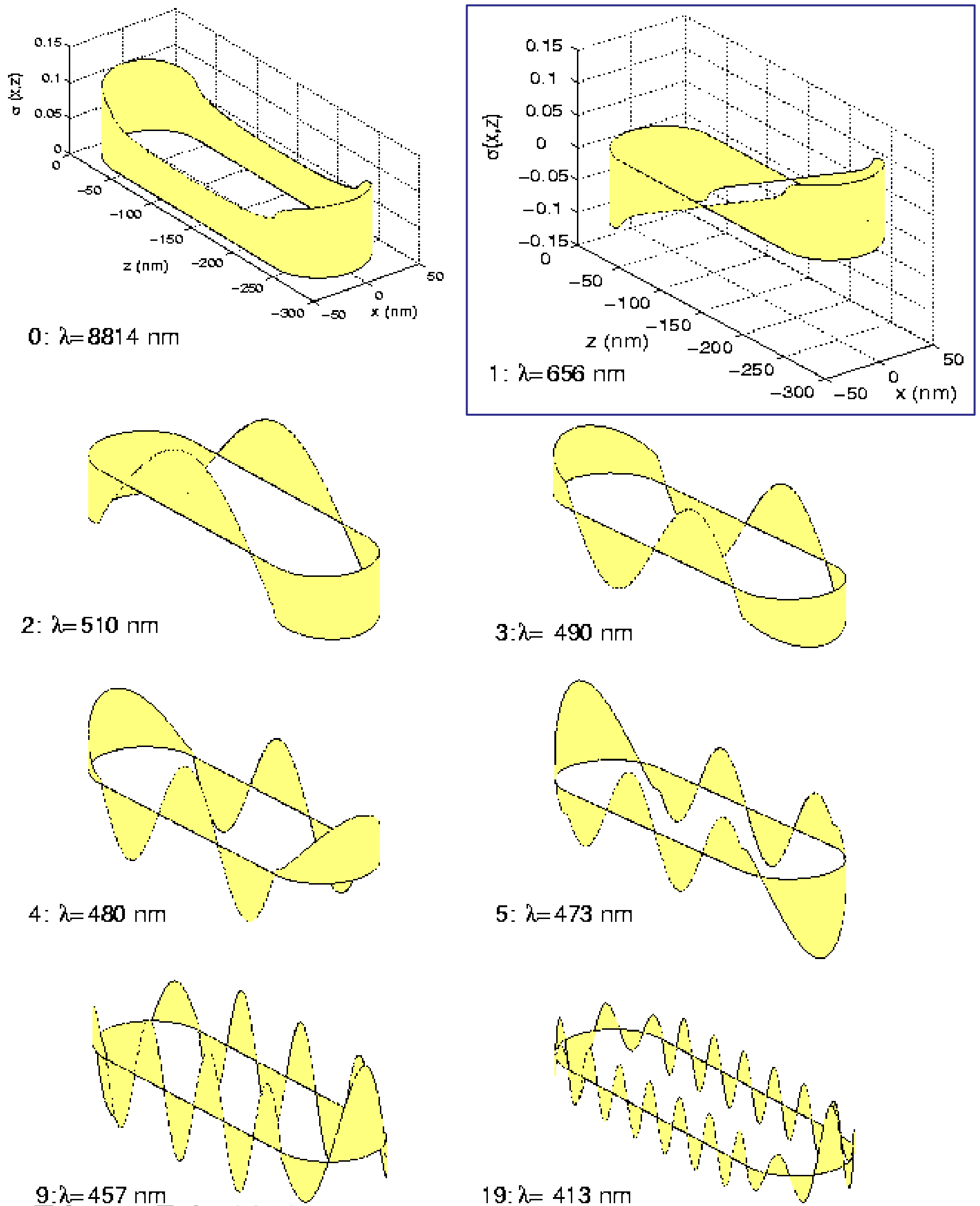
D=80nm,L=200nm; ratio=2.5

Dipole response:

L α λ/2

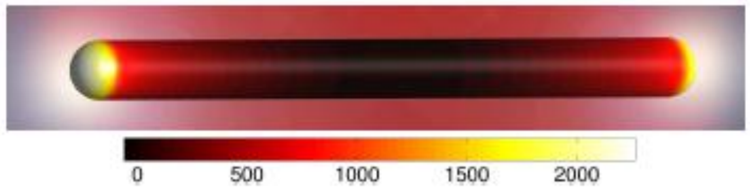




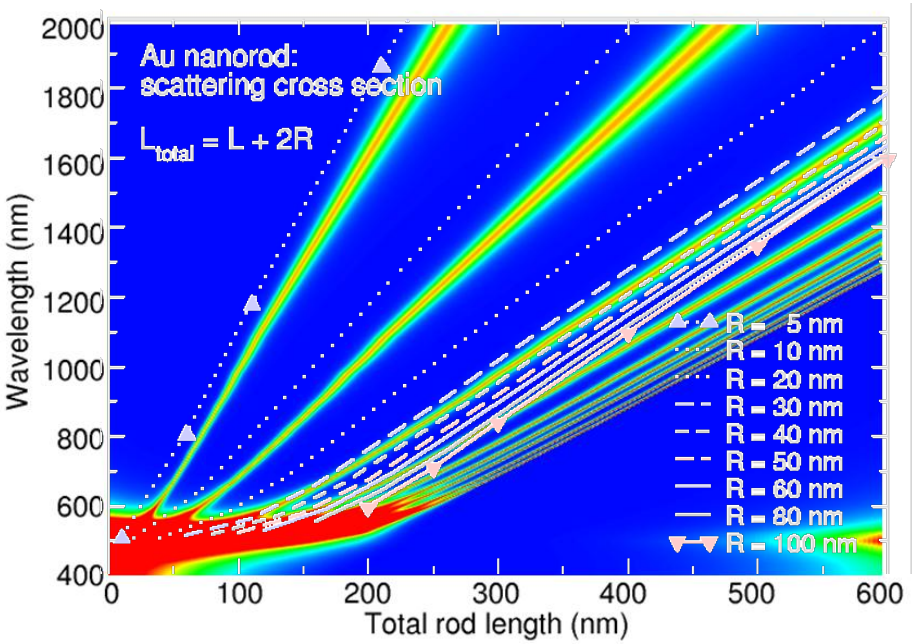


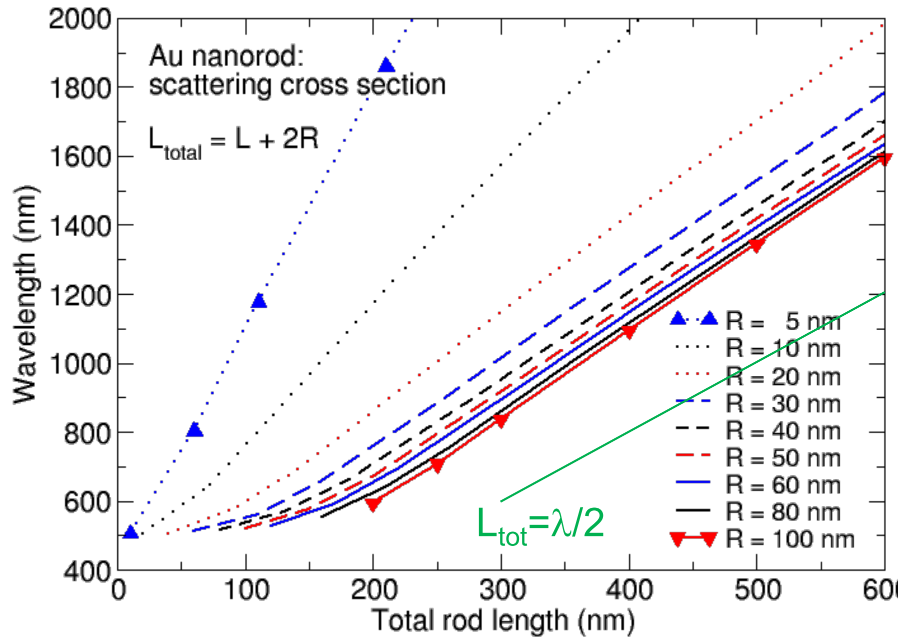
Aizpurua et al. Physical Review B 71, 235420 (2005)

Metallic nanorod as a λ/2 optical antenna



Mapping the plasmon resonances of metallic nanoantennas





$$(q^2 - \varepsilon k^2)^{1/2}\, I_0((q^2 - \varepsilon k^2)^{1/2} R) K_1((q^2 - k^2)^{1/2} R) + \varepsilon\, (q^2 - k^2)^{1/2}\, I_1((q^2 - \varepsilon k^2)^{1/2} R) K_0((q^2 - k^2)^{1/2} R) = 0$$

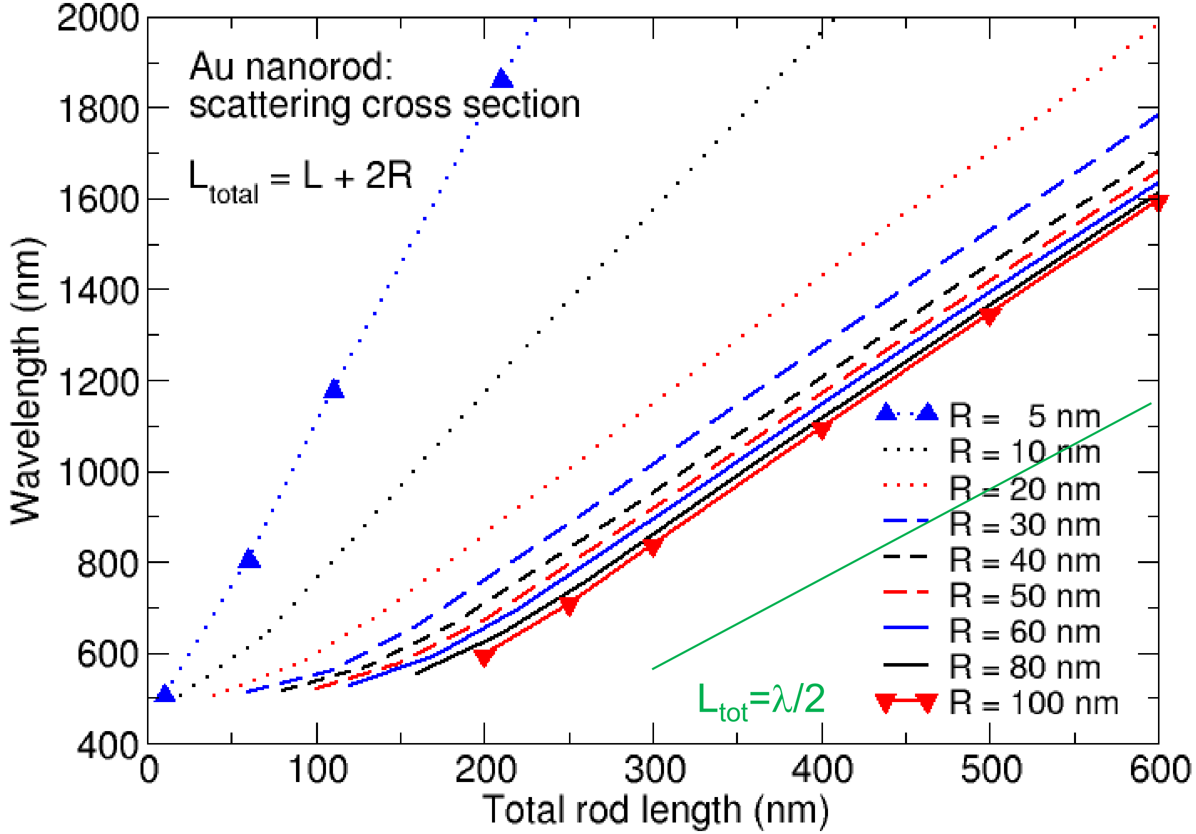
$$q = \pi / L_{tot}$$

G.W. Bryant, F.J. García de Abajo and J. Aizpurua, Nano Lett. **8**, 631 (2008)

Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

Dependence of the λ/2 antenna resonance with the length L

Au nanowire with hemispherical ends

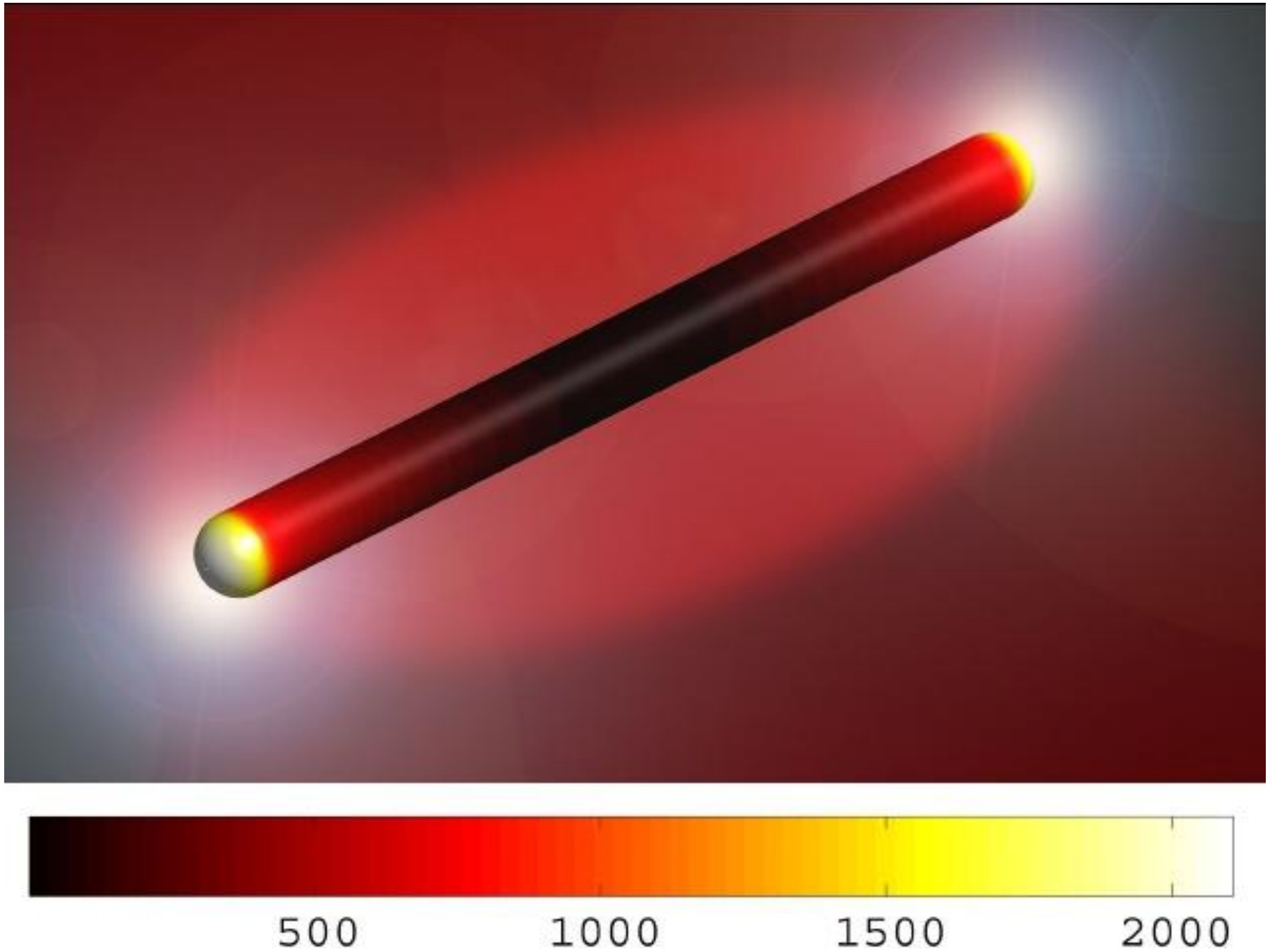


The resonance follows L α λ/3 - λ/10 !!!!; not like in ideal antenna theory L α λ/2

Aizpurua et al. Physical Review B **71**, 235420 (2005); L. Novotny, Phys. Rev. Lett. **98**, 266802 (2007)

G.W. Bryant, F.J. García de Abajo and J. Aizpurua, Nano Lett., **8**, 631 (2008)

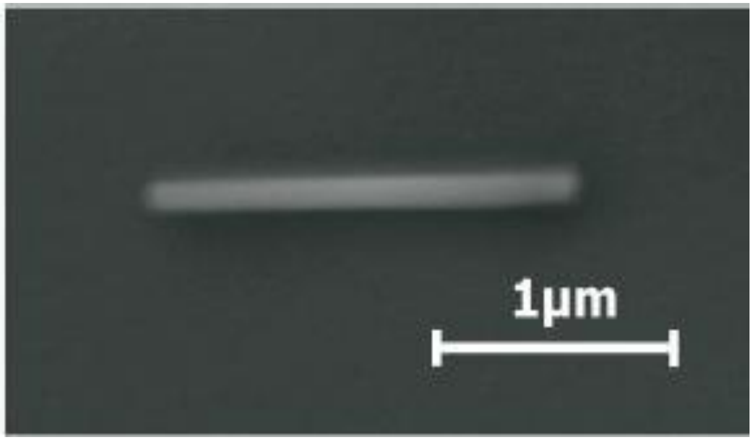
Optical nanoantenna resonant at λ=3.41μm with L=1.31μm and D=100nm



Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

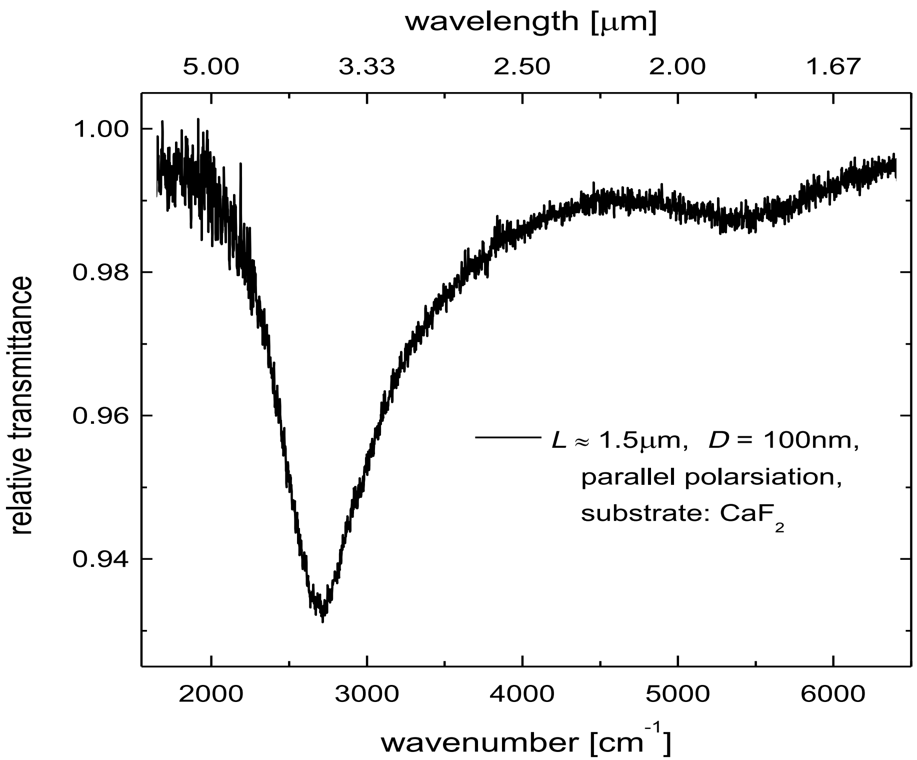
Finding the right nanowire resonance for IR spectroscopy

Experiments by Prof. A. Pucci's group (Heidelberg, Germany)



Gold nanowire (L=1.5µm and D=100nm, on a silicon wafer)

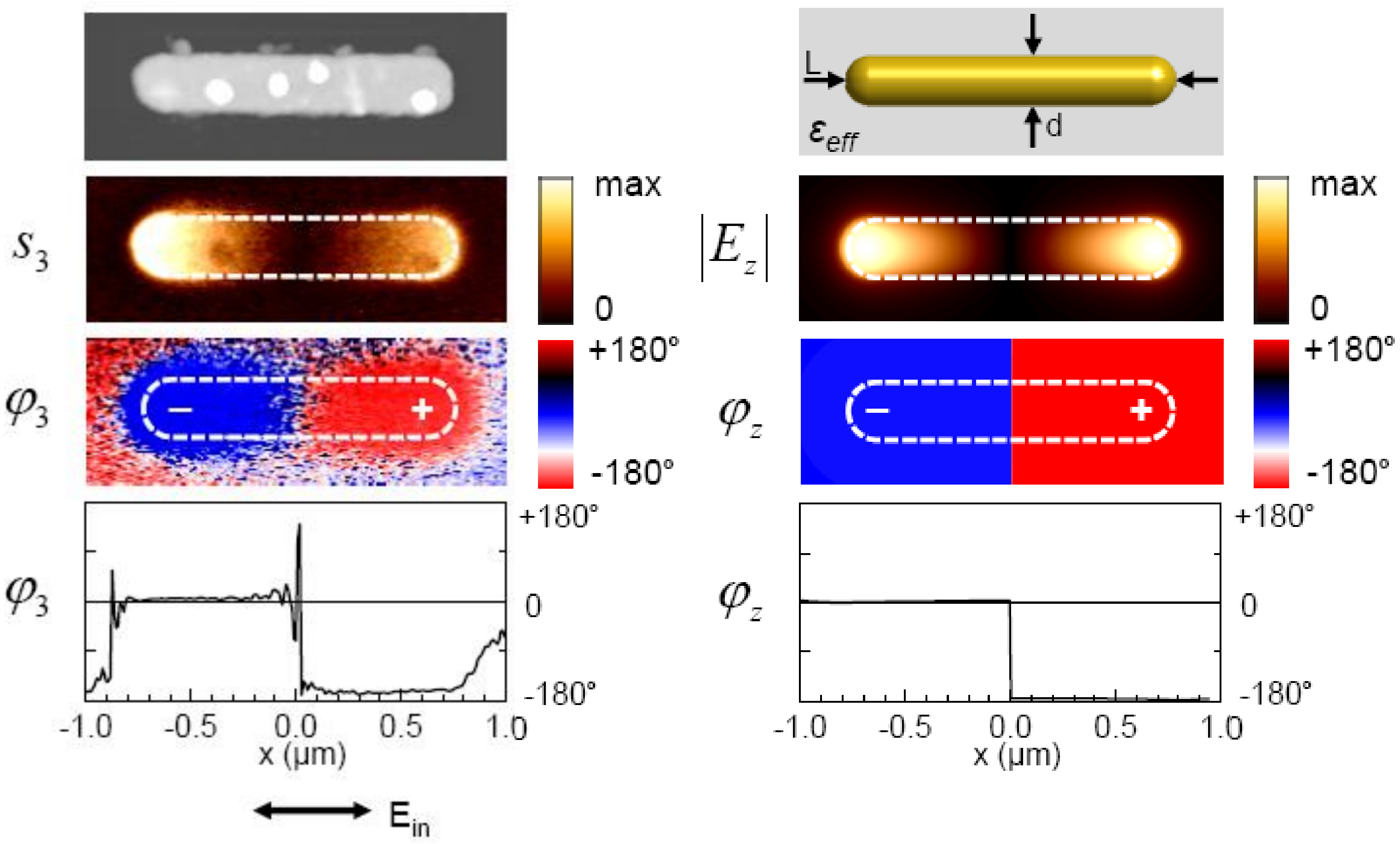
SEM image: perfect cylindrical shape



Relative IR transmittance spectra
Electric field along the long wire axis

F. Neubrech et al. Appl. Phys. Lett. 89, 253104 (2006)

Near-field mapping of IR nanoantennas



Experiment by Martin Schnell, R. Hillenbrand's group

Calculation by A. Garcia-Etxarri, San Sebastian

M. Schnell *et al.*, Nature Photonics 3, 287 (2009)

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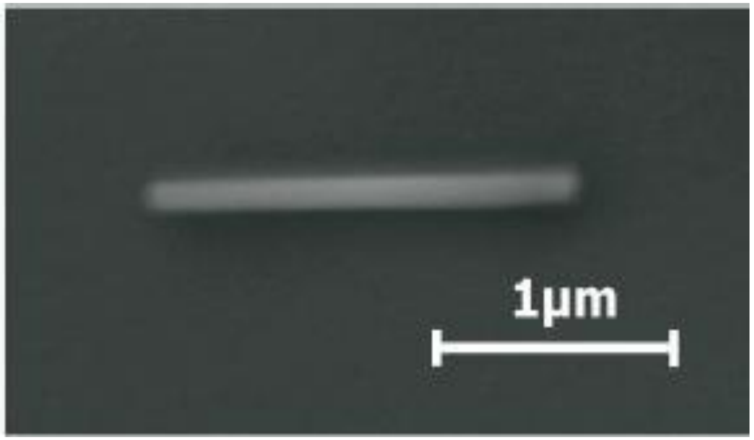
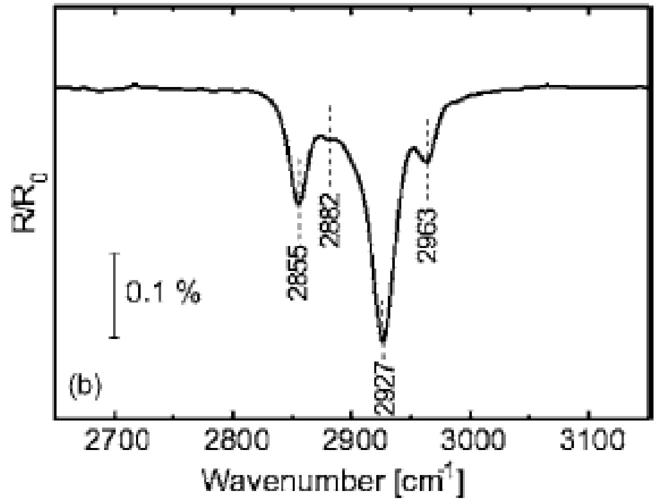


Gold nanowire (L=1.7μm and D=100nm, on a silicon wafer)

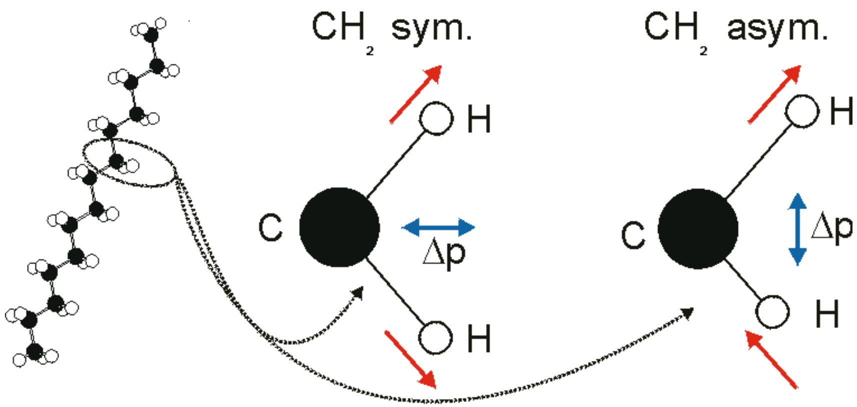
SEM image: perfect cylindrical shape

F. Neubrech et al. Appl. Phys. Lett. 89, 253104 (2006)

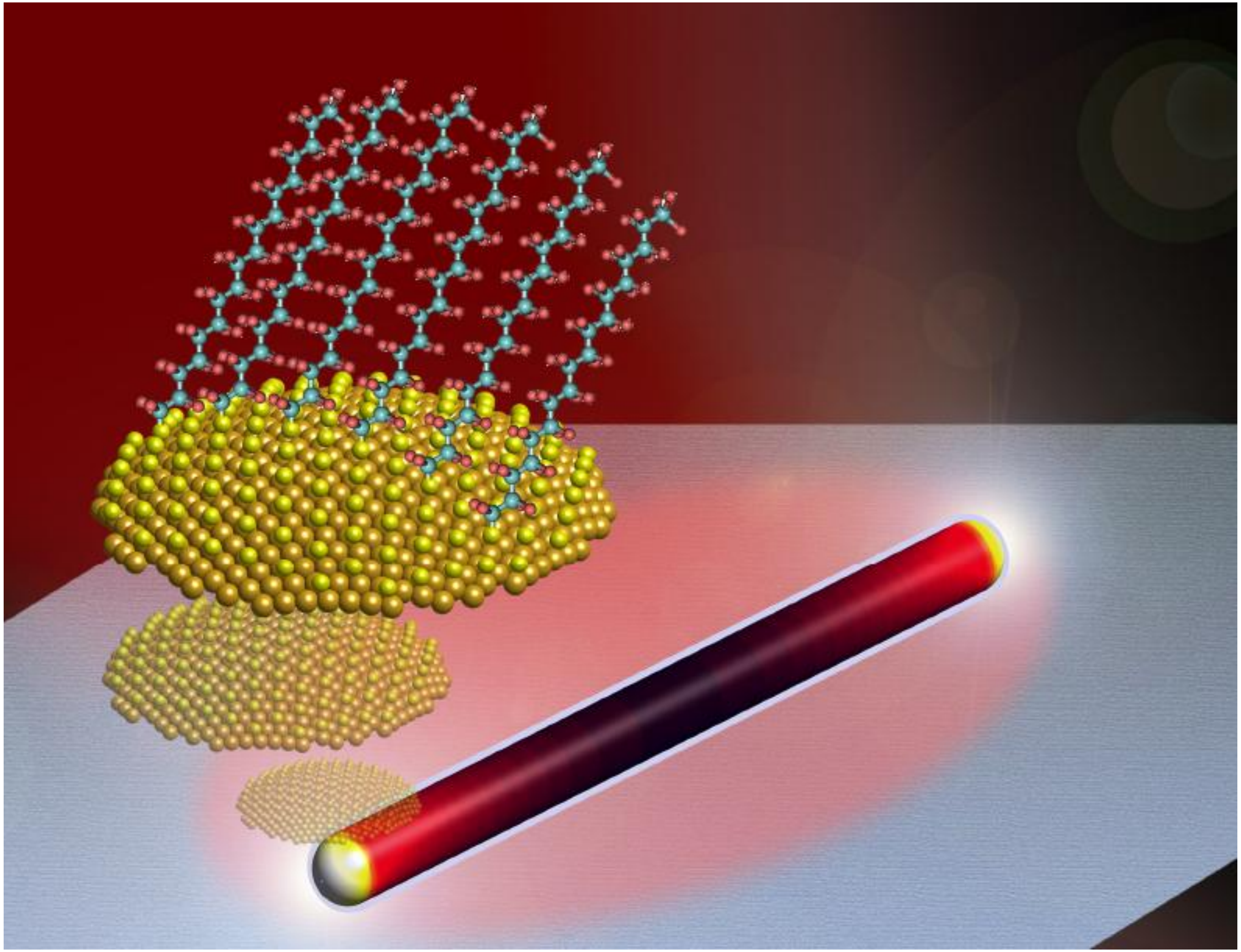
Absorption bands in ODT



Vibration modes in CH_2

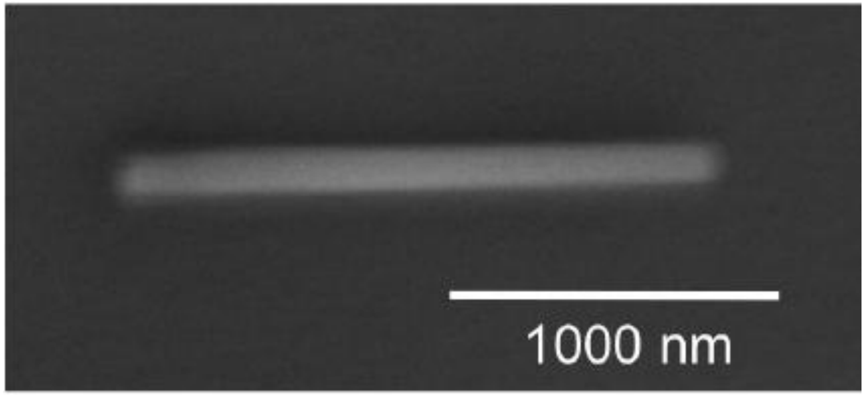


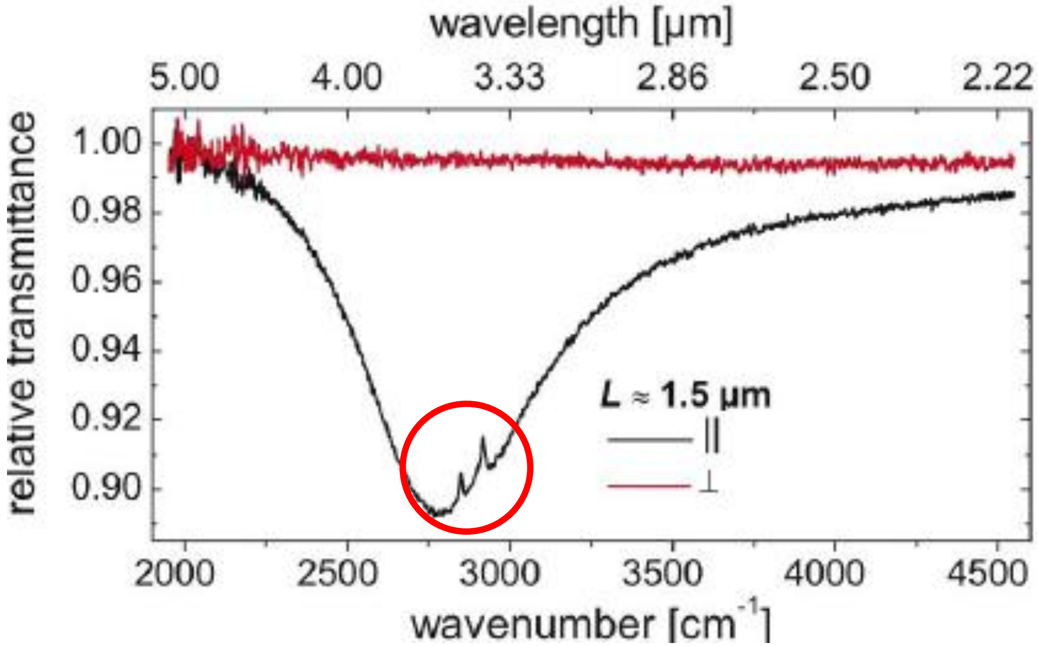
ODT covered nanoantenna



Sample and reference obtained in the spectral range of 600 cm^{-1} to 7000 cm^{-1} (res. 2 cm^{-1})

Relative IR transmitance of ODT molecules on a gold nanowire

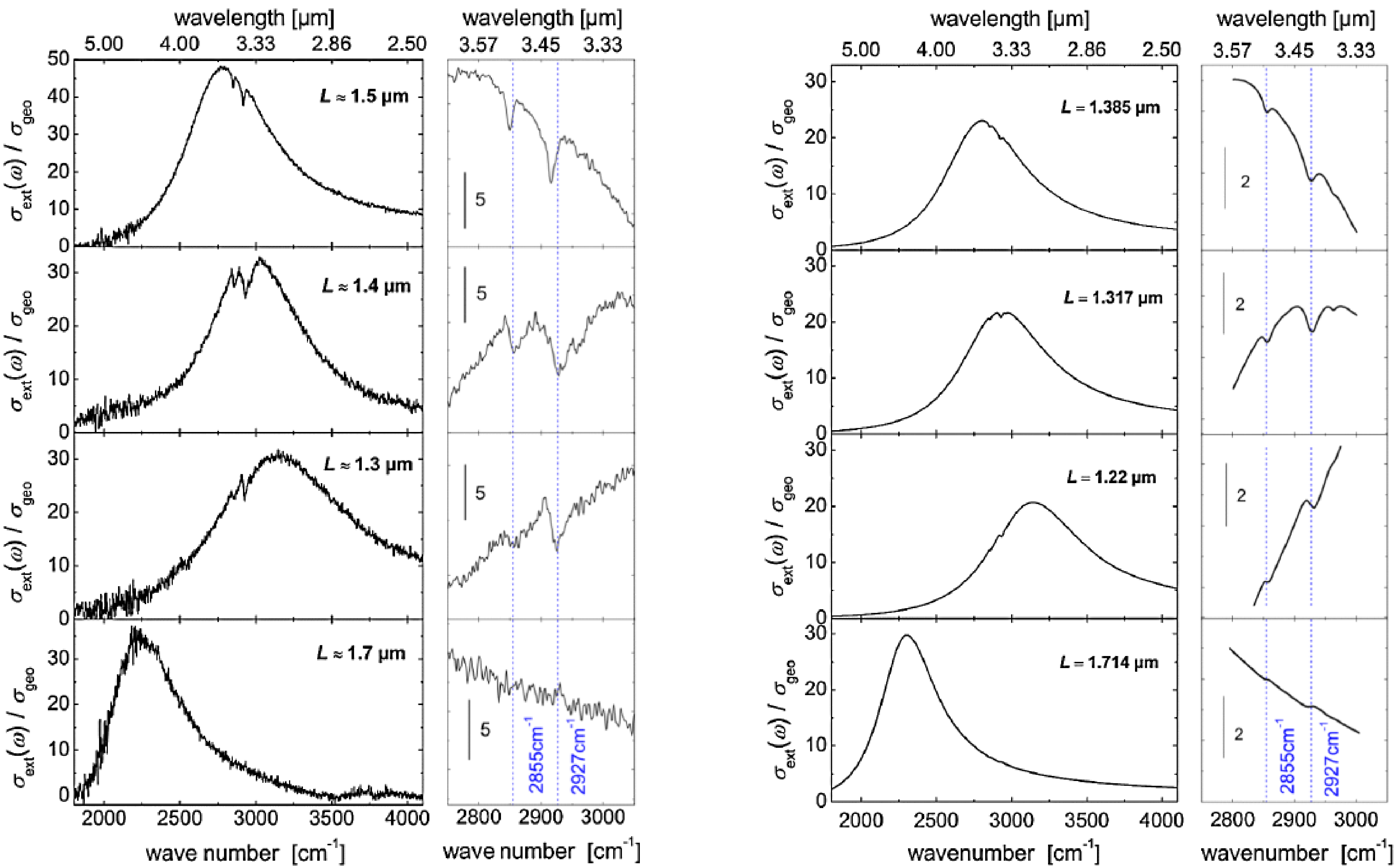




F. Neubrech et al. Phys. Rev. Lett. **101**, 157403 (2008)

Tailoring the nanoantenna for signal optimization

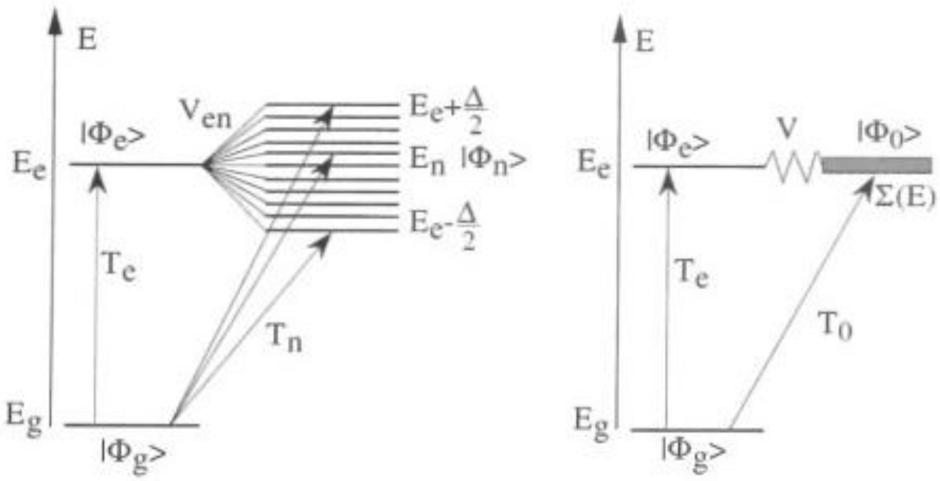
Experiments / Theory

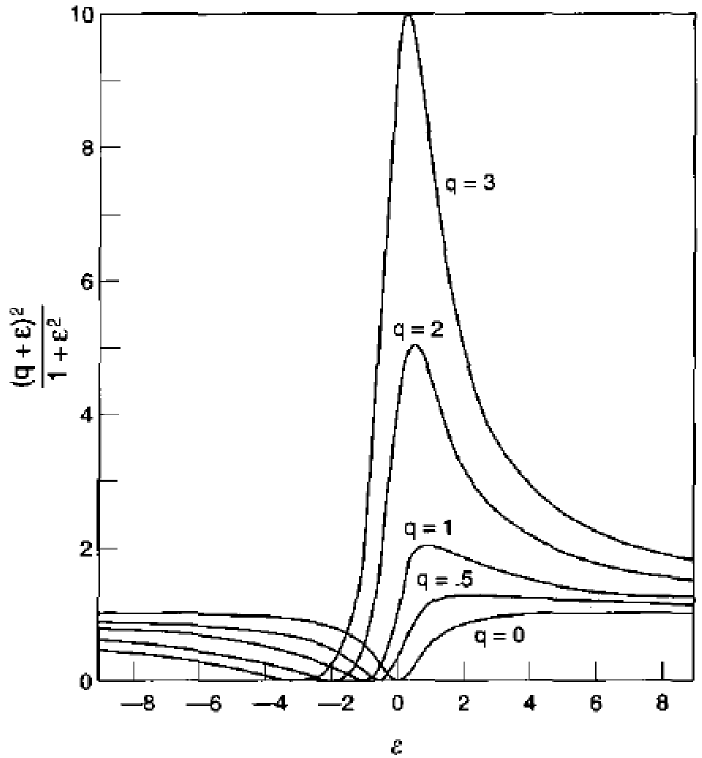


Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012 F. Neubrech et al. Phys. Rev. Lett. **101**, 157403 (2008)

Classical analog of Fano effect

Discrete state coupled to a continuum





$$|T_F(q,\omega)|^2 = |T_o|^2 \frac{(\omega-\omega_o' + \Gamma q)^2}{(\omega-\omega_o')^2 + \Gamma^2}$$

$$= |T_o|^2 \left(1 + \frac{2q\Gamma\left(\omega-\omega_o'\right) + \Gamma^2(q^2-1)}{(\omega-\omega_o')^2+\Gamma^2}\right)$$

$$\Gamma = 2\pi \frac{|V|^2}{\Delta} \qquad \varepsilon = \frac{\omega-\omega_o'}{\Gamma/2} \qquad q = \frac{1}{\pi}\frac{T_e}{T_o}\frac{\Delta}{V}$$

$$|T_F|^2 = |T_o|^2 \frac{1}{\Delta}\frac{|\varepsilon+q|^2}{\varepsilon^2+1} = |T_o|^2 \frac{1}{\Delta}\left[1+\frac{q^2}{\varepsilon^2+1}+\frac{2q\varepsilon-1}{\varepsilon^2+1}\right]$$

Classical analog of Fano effect

Discrete state coupled to a continuum

$$|T_F(q,\omega)|^2 = |T_o|^2 \frac{(\omega-\omega_o' + \Gamma q)^2}{(\omega-\omega_o')^2+\Gamma^2}$$

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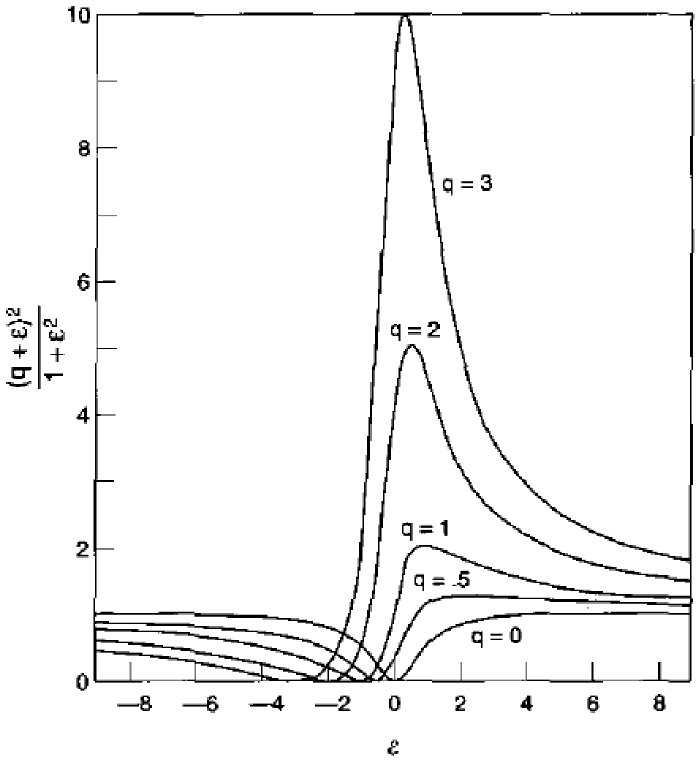
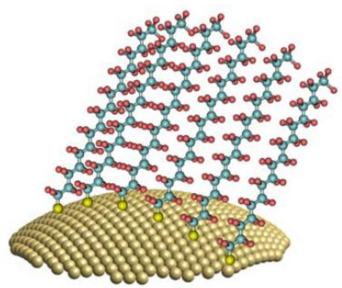
$$\boxed{|T_F|^2 = |T_o|^2 \frac{1}{\Delta}\frac{|\varepsilon+q|^2}{\varepsilon^2+1} = |T_o|^2 \frac{1}{\Delta}\left[1 + \frac{q^2}{\varepsilon^2+1} + \frac{2q\varepsilon-1}{\varepsilon^2+1}\right]}$$



Electromagnetic interference

$$|T_t|^2 = |T|^2 \left(1 - 4\pi^2 \frac{d}{\lambda}\sqrt{\varepsilon_o}\, N\alpha_o\omega_o R^i \frac{(\omega-\omega_o) + \frac{1+R^r}{R^i}\frac{\gamma}{2}}{(\omega-\omega_o)^2 + \left(\frac{\gamma}{2}\right)^2}\right)$$

$$\frac{1+R^r}{R^i} = \frac{q^2-1}{2q}$$



Optical antennas: Spectroscopy, Microscopy and other applications

Javier Aizpurua

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universidad del pais vasco

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

http://cfm.ehu.es/nanophotonics

Center for Materials Physics, CSIC-UPV/EHU

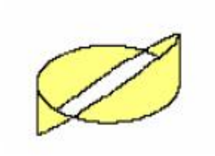
and Donostia International Physics Center - DIPC

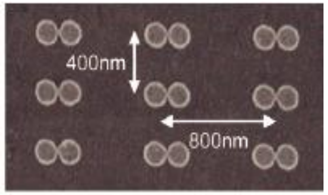
Donostia-San Sebastián, the Basque Country, Spain

Winter College on Optics: Advances in Nano-Optics and Plasmonics
February 6-17, 2012
The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

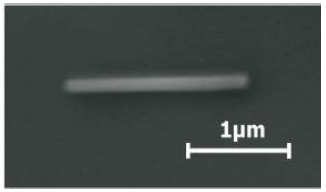
Outline

- Optical antennas: Basics

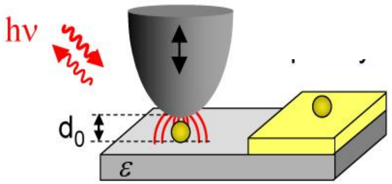




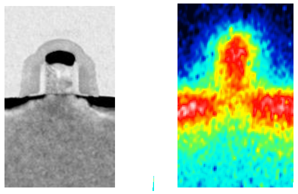
- Playing with antenna modes



- Optical antennas for Enhanced Spectroscopy

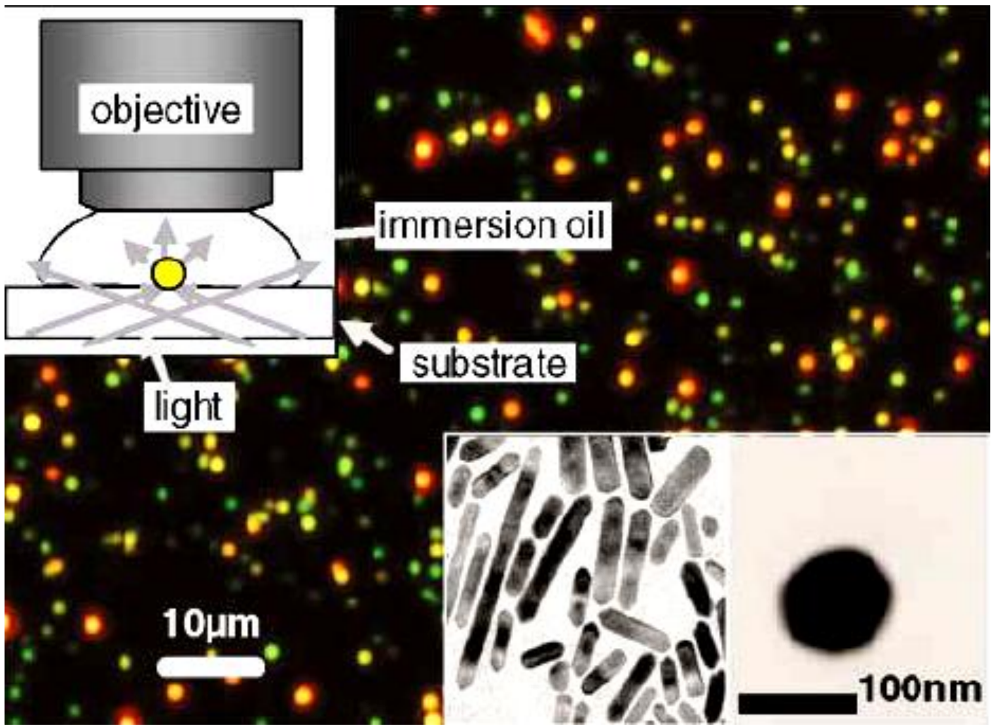


- More applications of optical antennas: Microscopy and Biomedicine.



Near-field Optical Microscopy

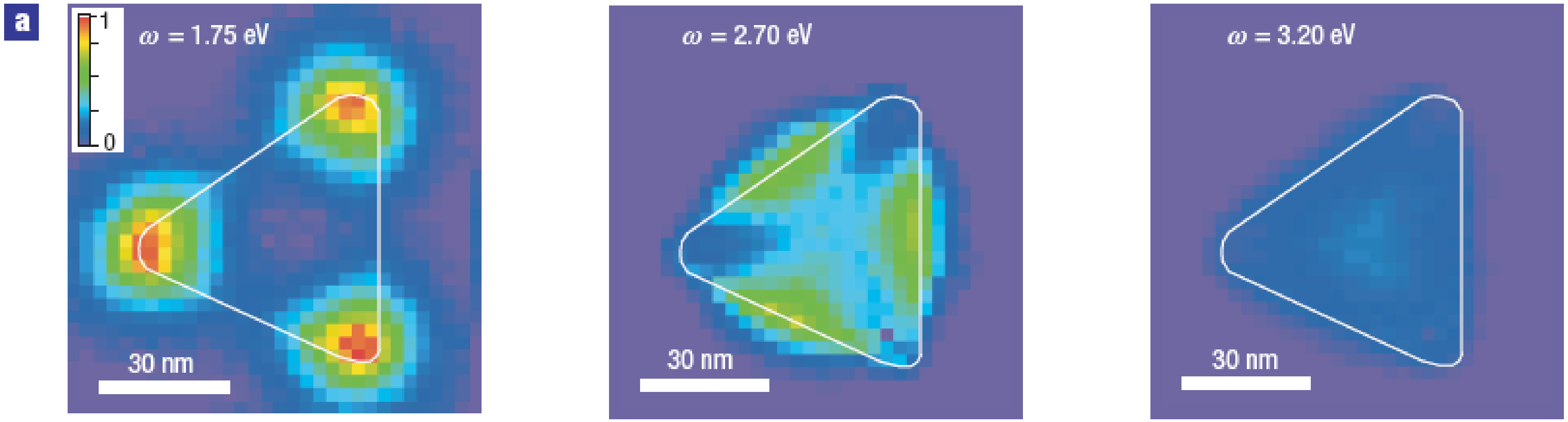
- **Far field information is commonly accesible:**
  - **Dark field optical spectroscopy**



C. Sönnichsen *et al.*, *Phys. Rev. Lett. 88*, *077402 (2002)*

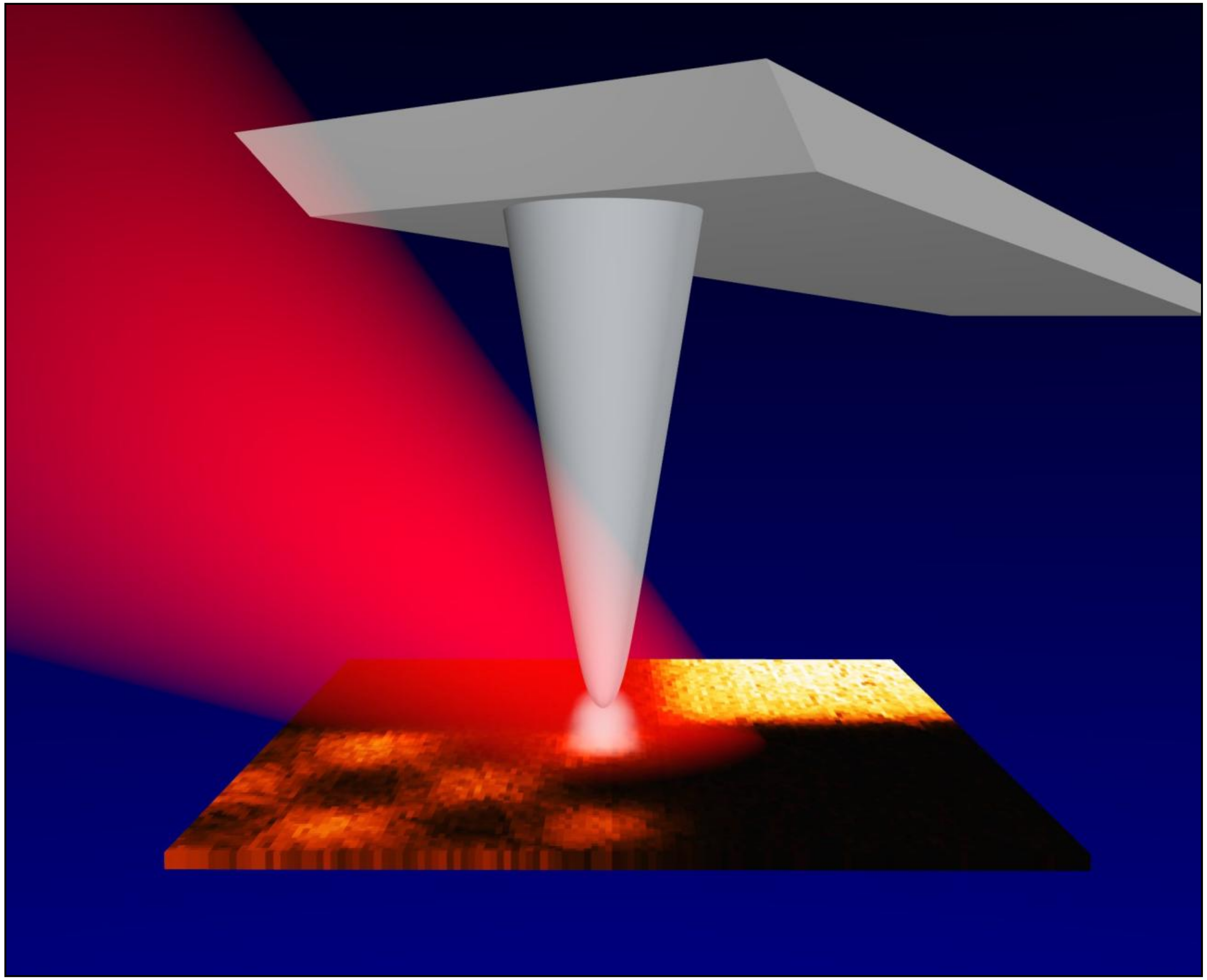
Near-field Optical Microscopy

- **Near-Field is more challenging to acess**
  - **One possibility: EELS**
    - **Does not resolve the phase**



J. Nelayah *et al.*, *Nature Physics 3, 348 (2007)*

Scattering–type Near Field Optical Microscopy;
Mapping both amplitude and phase in the nanoscale



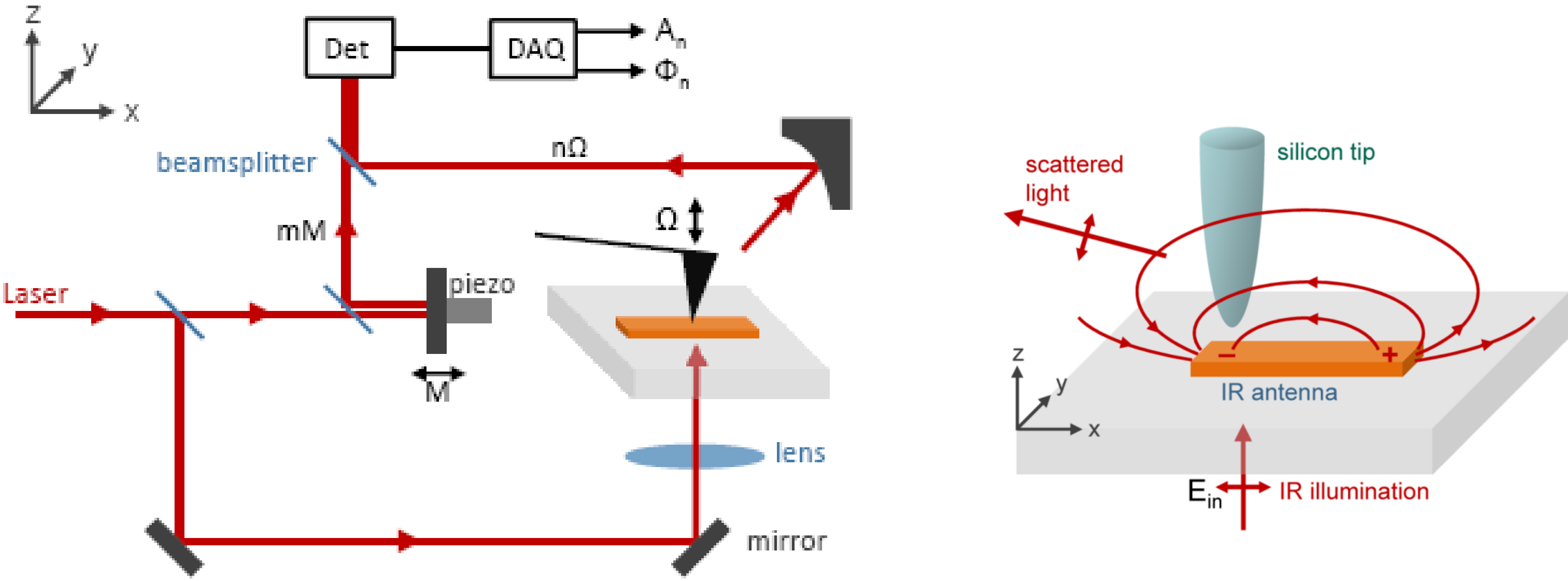
CIC nanoGUNE
nanoscience cooperative research center

Center for Nanoscience and Nanotechnology, San Sebastián, the Basque Country

Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

Transmision mode s-SNOM for near-field mapping

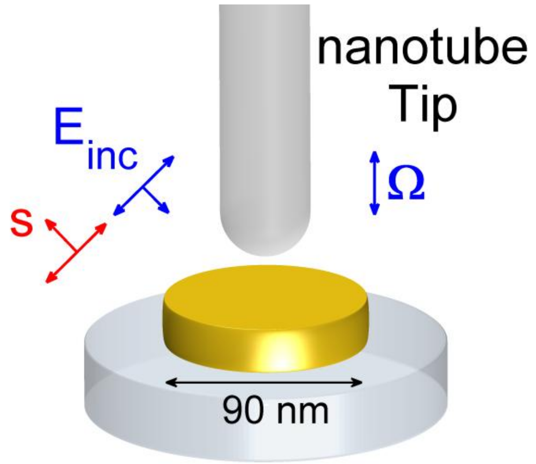
Rainer Hillenbrand



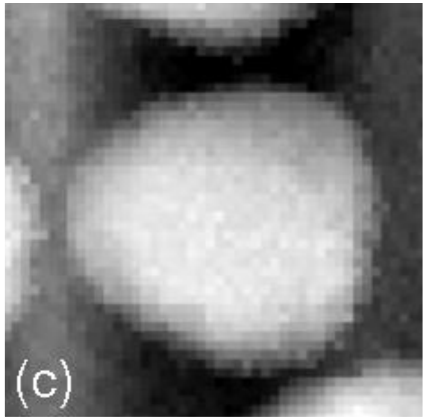
- **Transmission-mode for homogeneous illumination, also side illumination**
- **AFM tip scatters antenna near fields** **R. Hillenbrand et al. APL 83 (2003)**
- **Pseudoheterodyne detection measures amplitude and phase** ***APL.* 89 (2006)**

Which scattering tip to use?

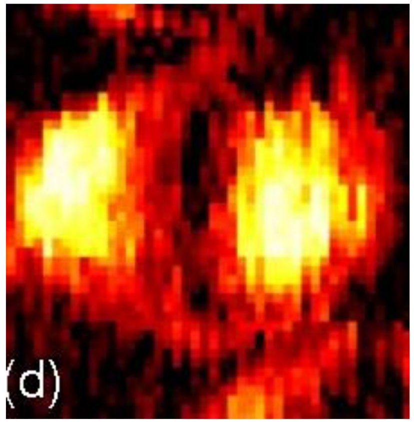
Weakly interacting Tip



Topography

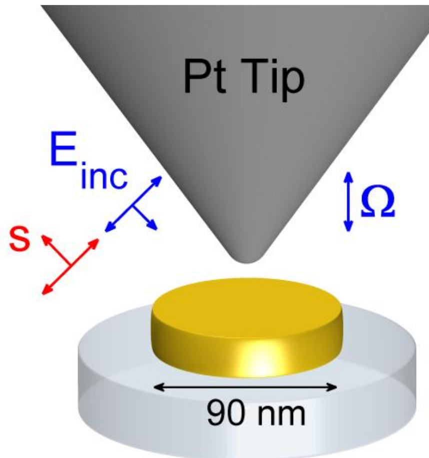


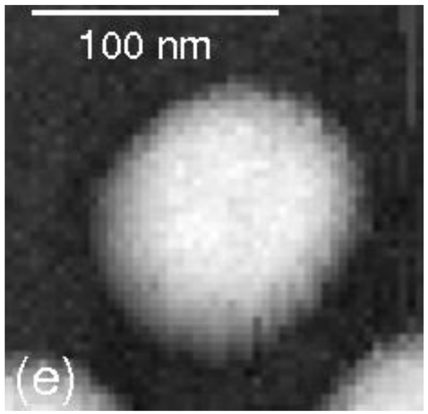
Near-field image

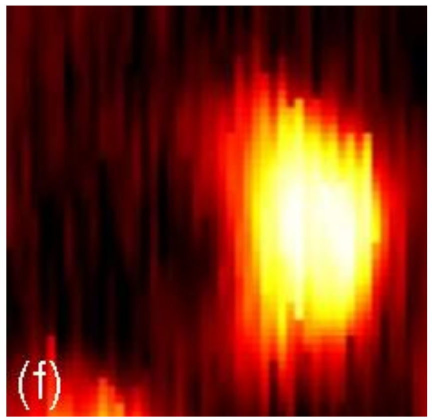


Experiments by R. Hillenbrand, nanoGUNE andMax Planck Institute (Donostia and Munich)

Strongly interacting Tip

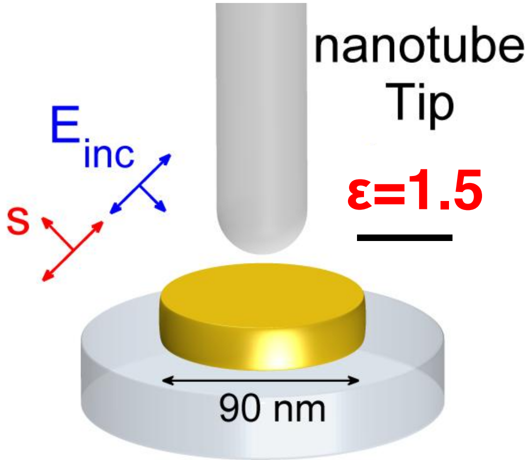






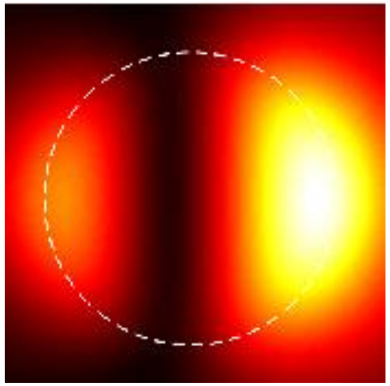
Which scattering tip to use?

Weakly interacting regime

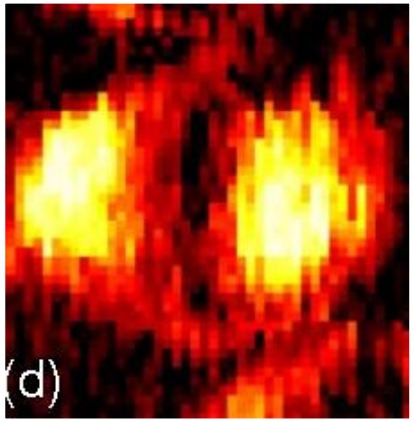


Theory

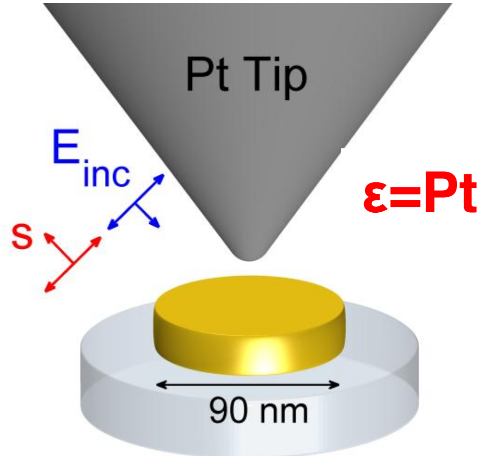
Original NF (no Tip)

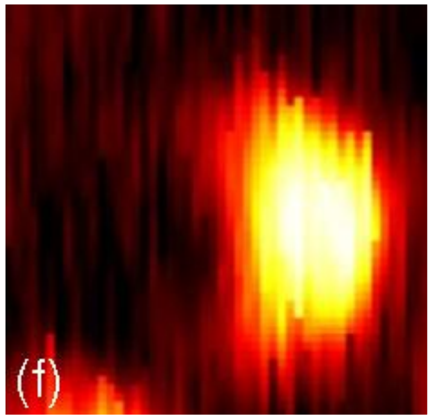


Experiment



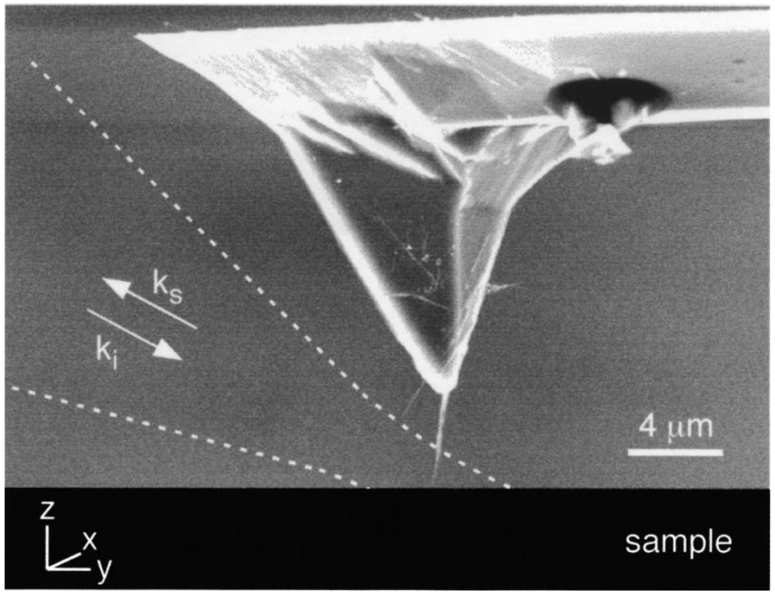
Strongly interacting regime

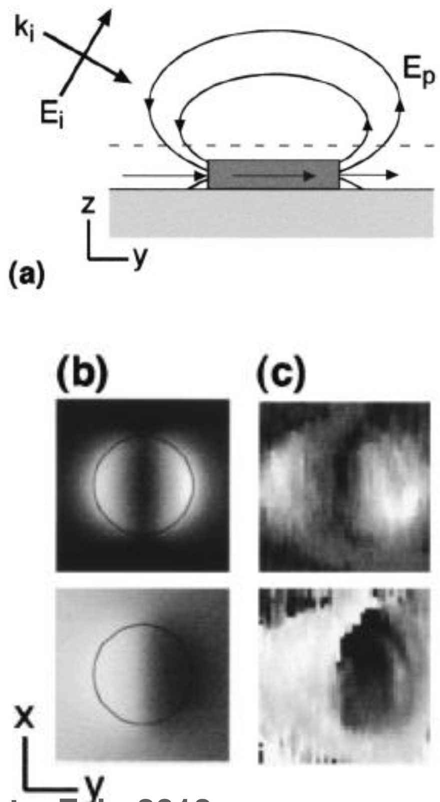




Accesing the NF information: s-SNOM weak scattering tip:carbon nanotube

- Scattering-type scanning near-field optical microscopy (s-SNOM) maps both amplitude and phase information in the nanoscale

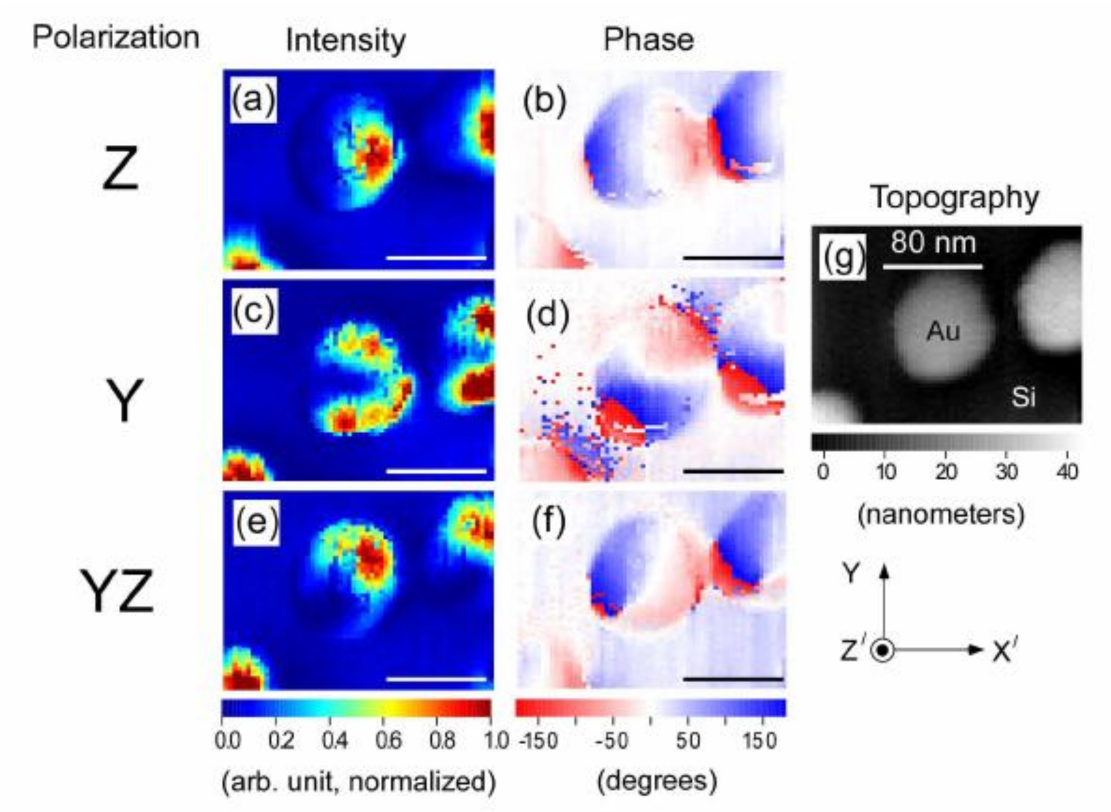




R. Hillenbrand *et al., Appl. Phys. Lett. 83, 368 (2003))*

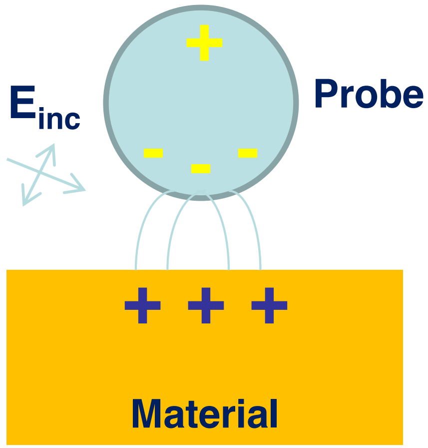
Accesing the phase information: s-SNOM

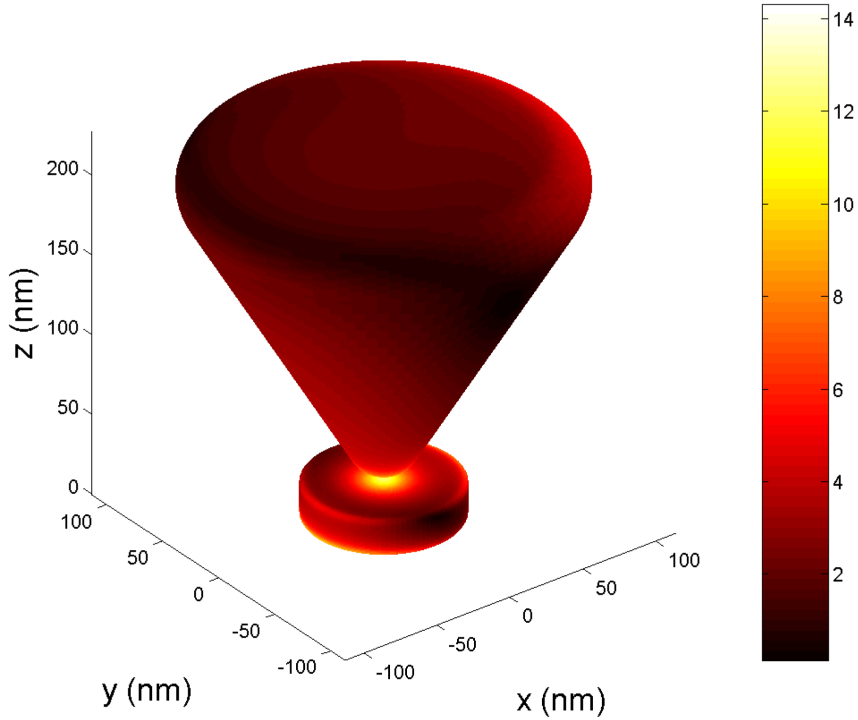
- Scattering-type scanning near-field optical microscopy (s-SNOM) maps both amplitude and phase information in the nanoscale



Z. H. Kim and S. R. Leone, Opt. Express 16, 1733 (2008)*)*

Any advantage of a strong scattering tip?

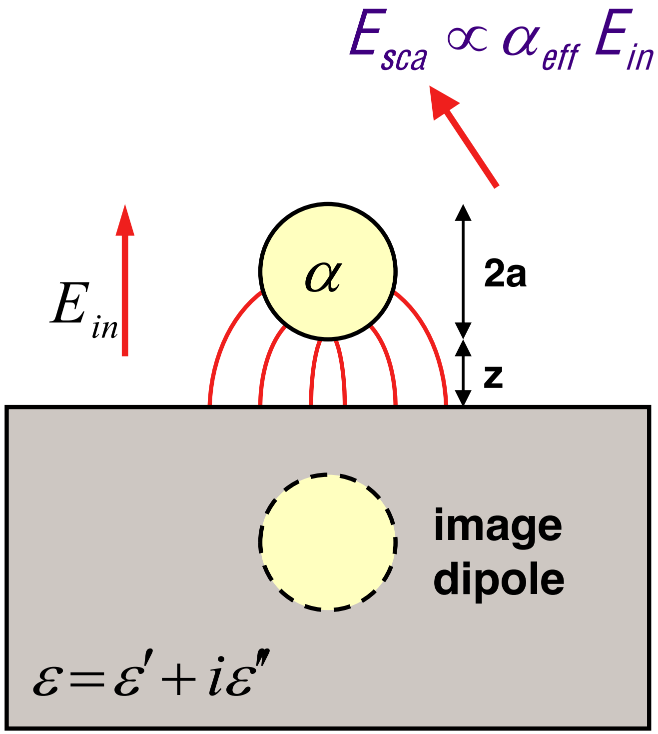




Material properties mapping

Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

Dipolar sphere-plane near-field interaction



Polarizability of the tip

$$\alpha = 4\pi a^3 \frac{\varepsilon - 1}{\varepsilon + 2}$$

Effective polarizability of interacting dipoles

$$\alpha_{eff} = \frac{\alpha(1+\beta)}{1 - \dfrac{\alpha\beta}{16\pi(z+a)^3}} \quad \textbf{with} \quad \beta = \frac{\varepsilon - 1}{\varepsilon + 1}$$

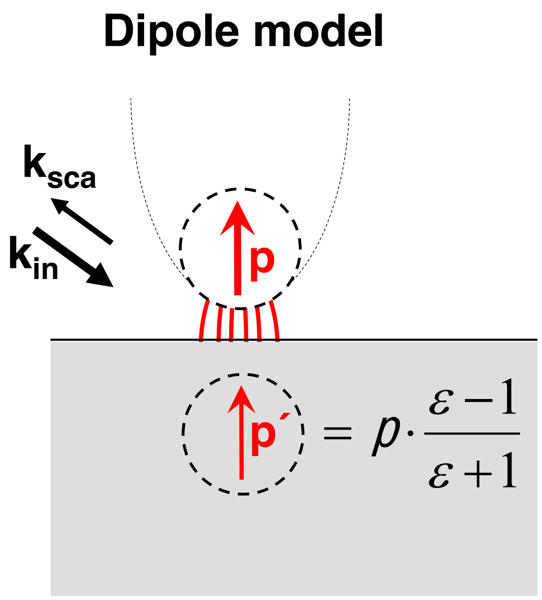
→ **near-field interaction modifies amplitude and phase of E_{sca}**

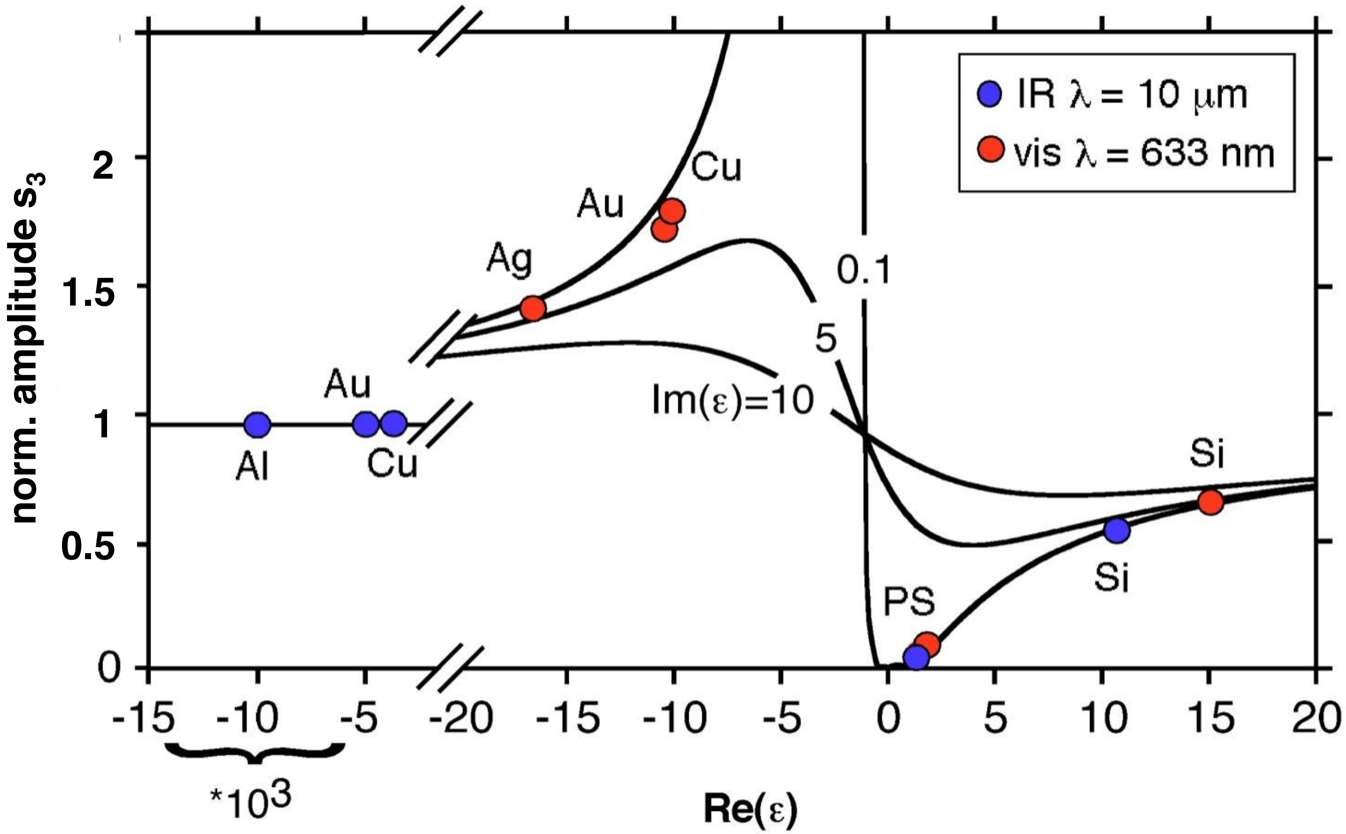
→ **resonance through a) sphere** $\varepsilon_p = -2$

b) plane $\varepsilon = -1$

No multipoles included in this description

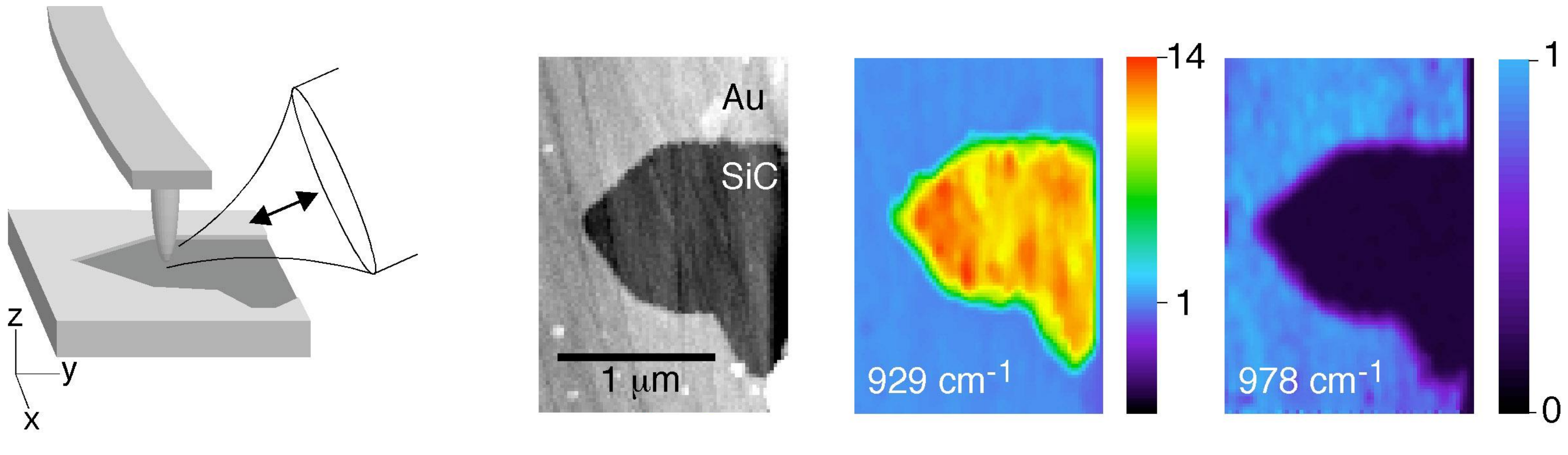
Dipole model explains near-field material contrasts from visible to IR frequencies





T. Taubner, R. Hillenbrand, F. Keilmann, J. Microsc. 210, 311 (2003)

s-SNOM contrast of SiC/Au



phonon-enhanced near-field interaction → **identification of materials at nanoscopic spatial resolution**

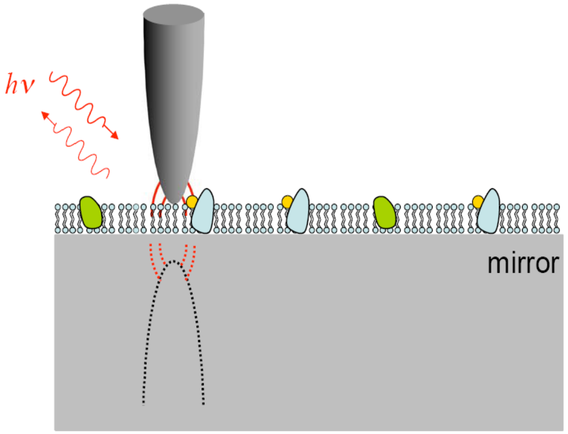
- strong signals
- high spectral sharpness
- optical fingerprint

< λ / 100 !

R. Hillenbrand, T. Taubner, F. Keilmann, Nature 418, 159-162 (2002)

Applications

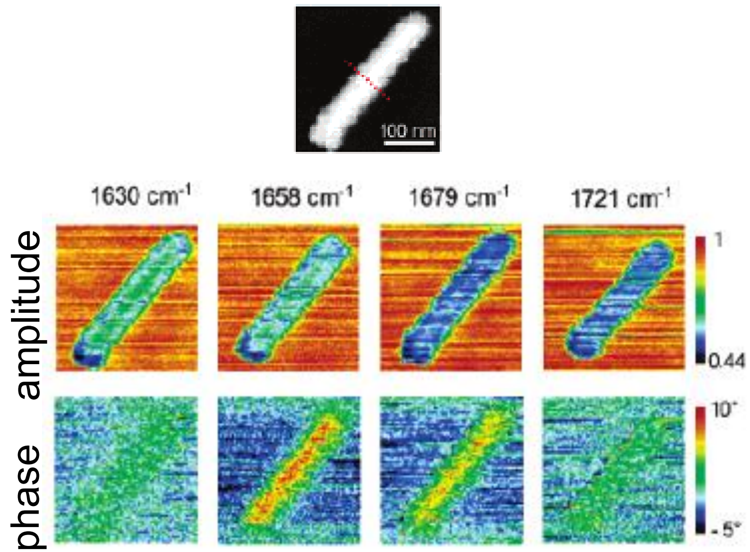
Hig resolution biolabeling imaging



Au particle→ biolabel

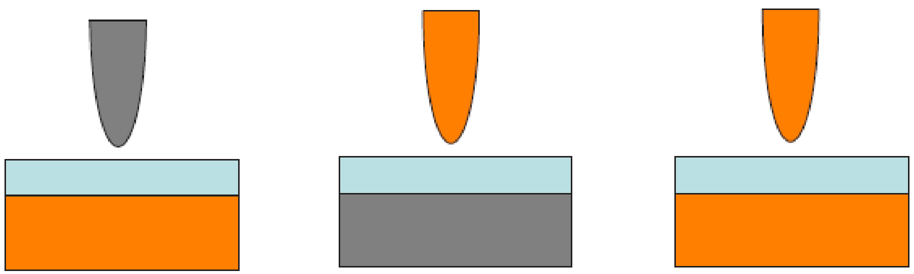
Resonant substrate→ mirror

IR near-field spectroscopy



IR Near-fiel imaging of a single tobacco virus on Si

M. Brehm et al, Nano Lett. **6**, 1307 (2006)



a) Resonant substrate

b) Resonant tip

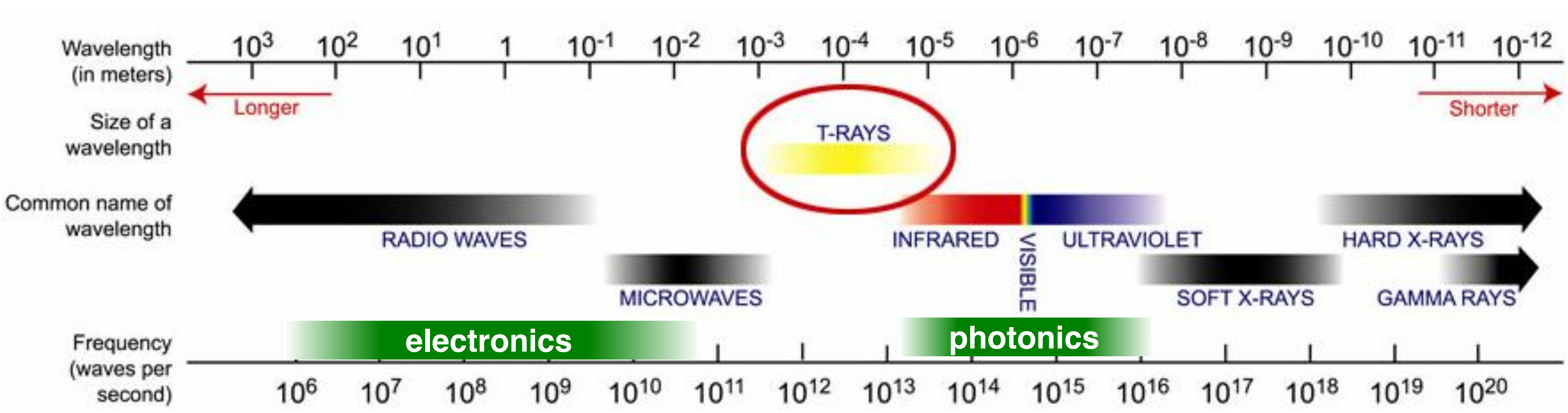
c) Resonant tip & substrate

Resonant structure or material

Sample layer with spectroscopic signature

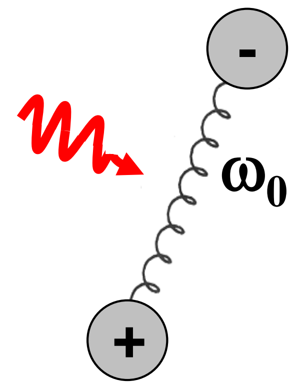
Non-resonant structure or material

Terahertz radiation (THz, T-RAYS)



Frequencies between IR and THz (far-IR) are highly sensitive to

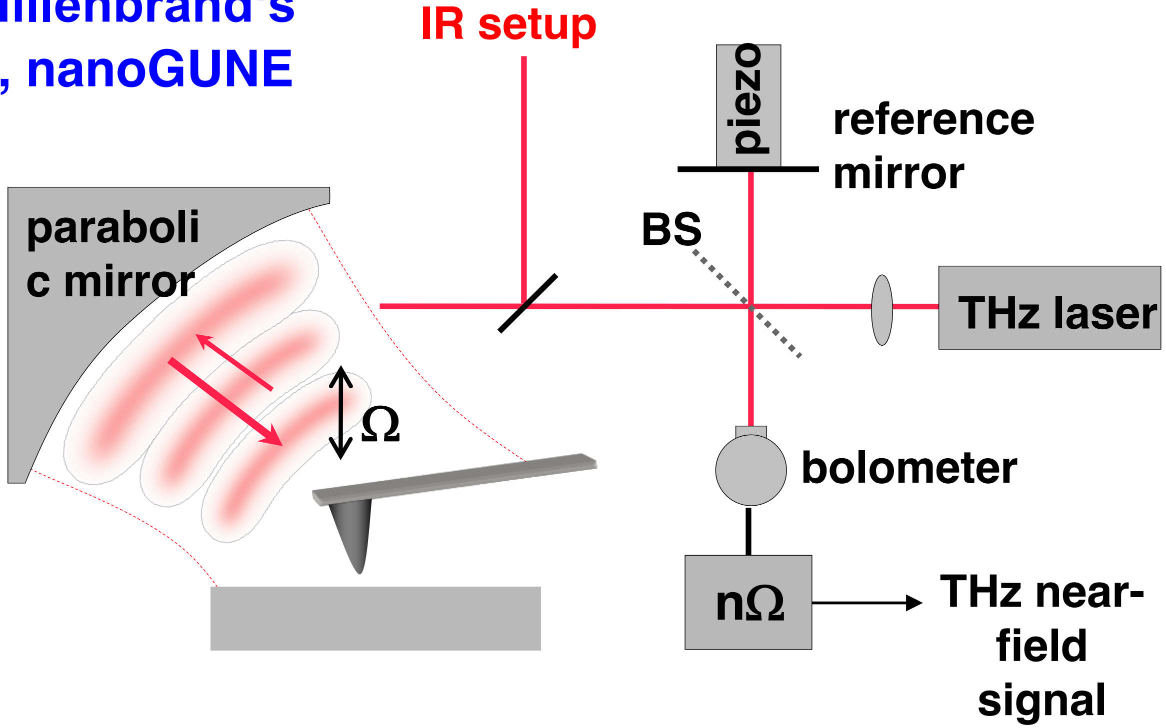
- **molecular vibrations → chemical composition**
- **crystal lattice vibrations → structural properties**
- **plasmons in doped semiconductors → electron properties**
- **.....**



BUT: spatial resolution > $\lambda/2 \approx$ 10-100 μm

Scattering-type THz near-field microscope based on AFM

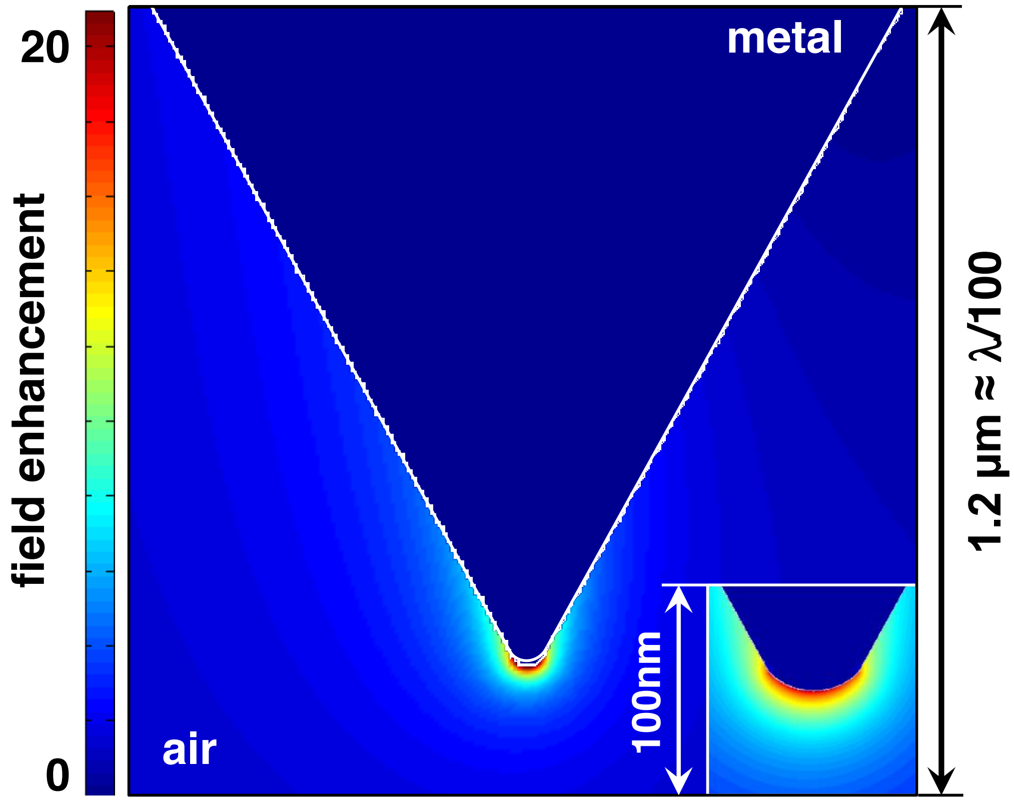
THz s-SNOM at R. Hillenbrand‘s group, nanoGUNE



- Use of commercial AFM tips (tip length L ≈ 10 - 20 μm << wavelength λ ≈ 100 -200 μm)
- Modulation of tip-sample distance (tapping mode, frequency Ω)
- Interferometric detection of THz radiation backscattered by tip
- Background suppression by signal demodulation at higher harmonics nΩ
- Use of single laser frequency (high laser power, ca. 100 mW)
- Integration in existing s-SNOM setup: simultaneous THz and IR s-SNOM

Theory predicts nanoscale confined THz fields

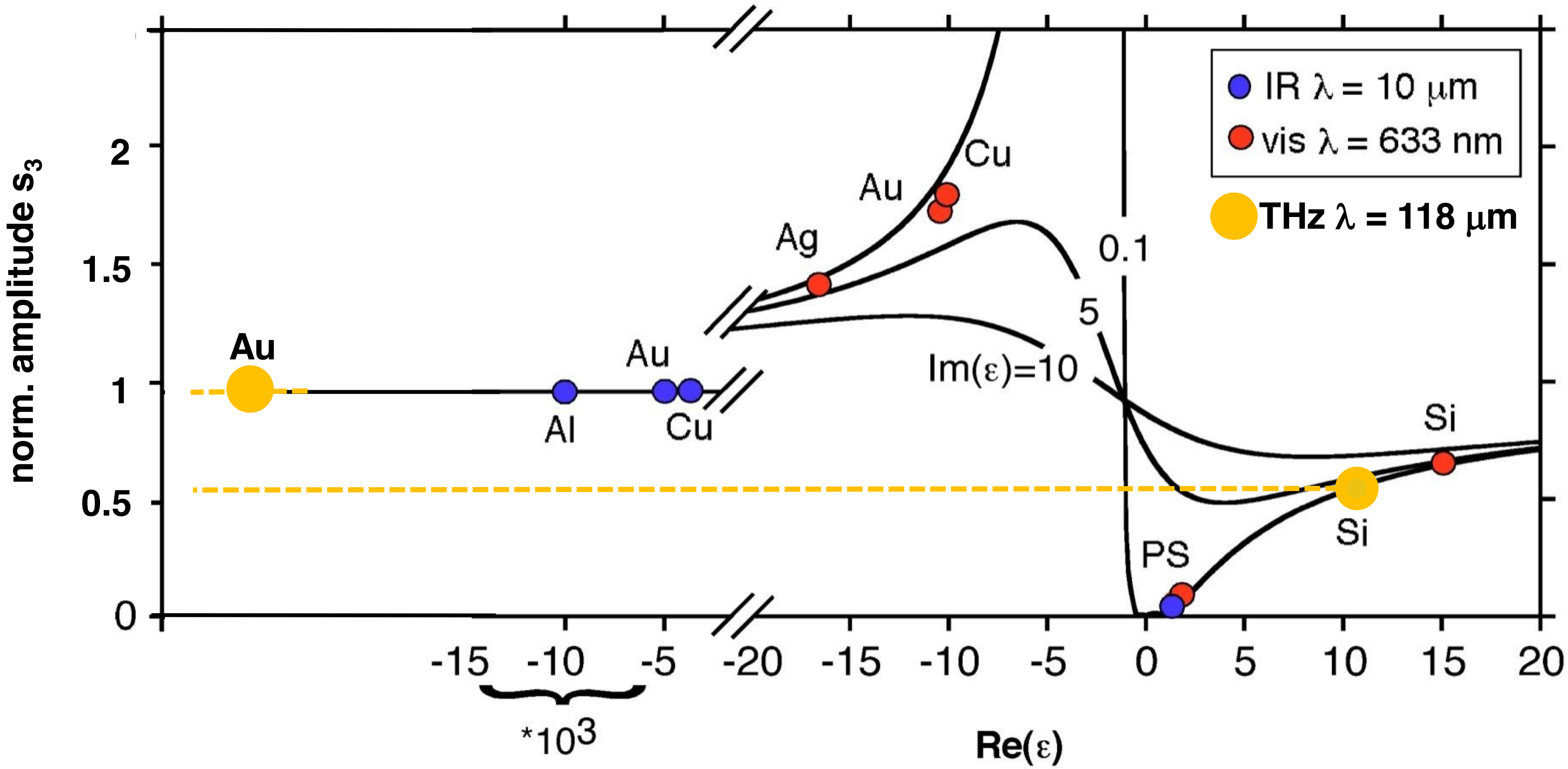
- Full electrodynamic calculation
- for 2.54 THz (λ ≈ 118 µm) predicts field enhancement at tip apex
- Tip length: 1 µm (≈ λ / 118)
- 30 nm field confinement at tip apex, like for VIS or IR frequencies
- Mechanism: lightning-rod effect



Boundary Element Method calculation

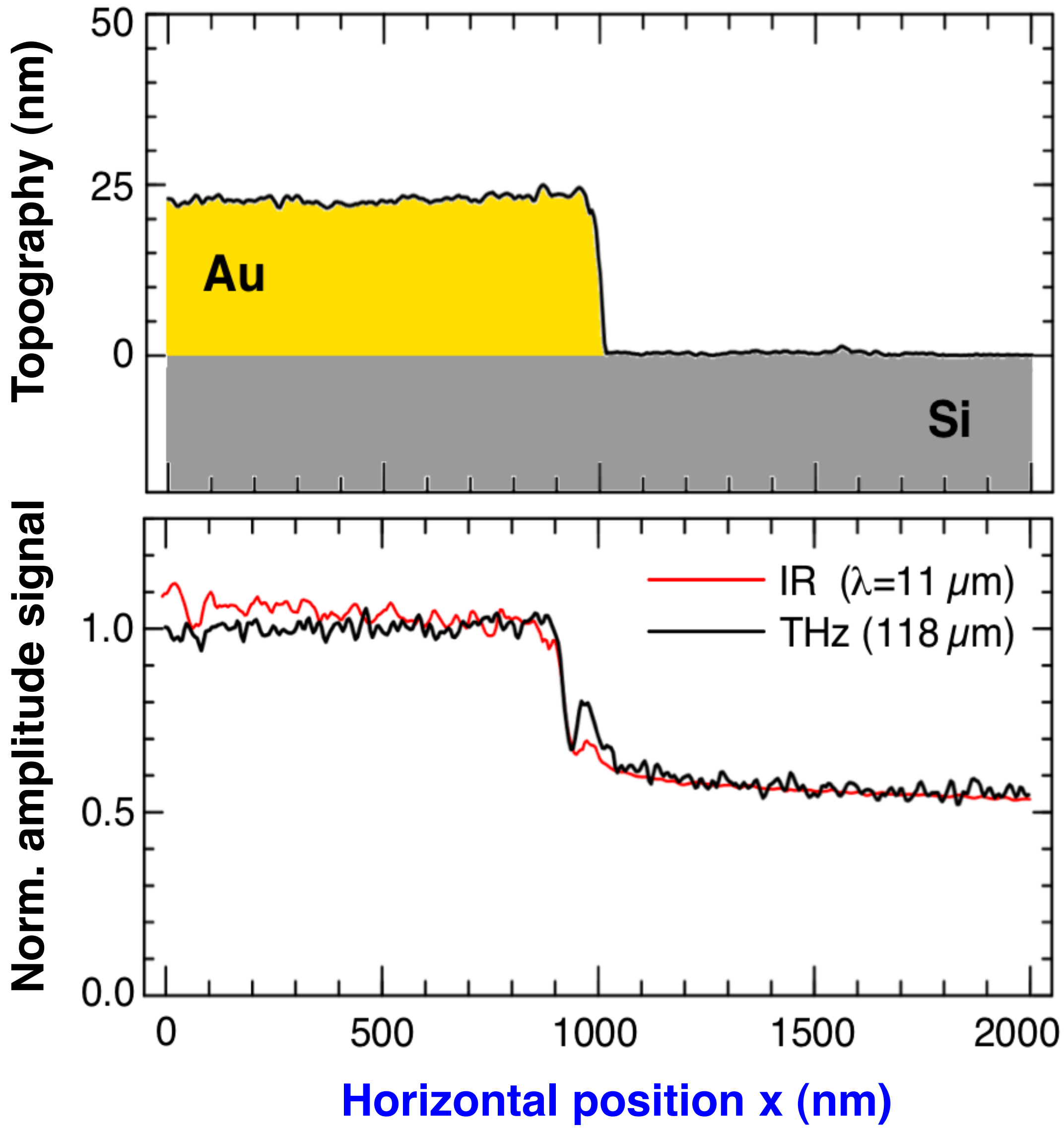
→ nanoscale confinement of THz fields can be achieved with metal tips much smaller than the wavelength, e.g. AFM tips

Dipole model explains near-field material contrasts from visible to THz frequencies



T. Taubner, R. Hillenbrand, F. Keilmann, J. Microsc. 210, 311 (2003)

Au/Si test sample demonstrates strong THz material contrast



Recording THz signal as a function of tip-sample position x:

Optical properties for Au and Si are the same at THz and IR frequencies

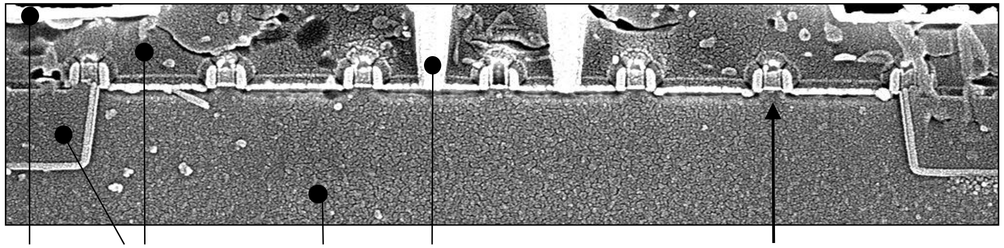
➔

similar near-field contrast mechanism at IR and THz frequencies

Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

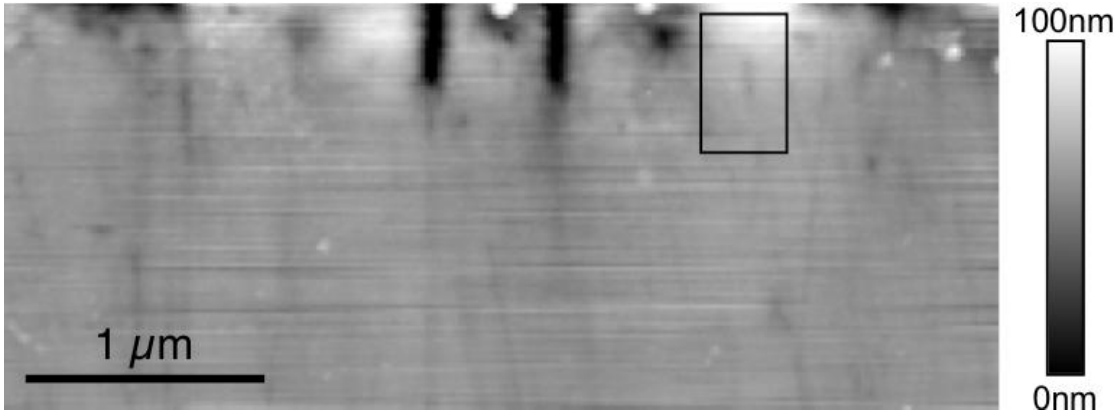
THz s-SNOM can map free carriers in semiconductor devices

SEM

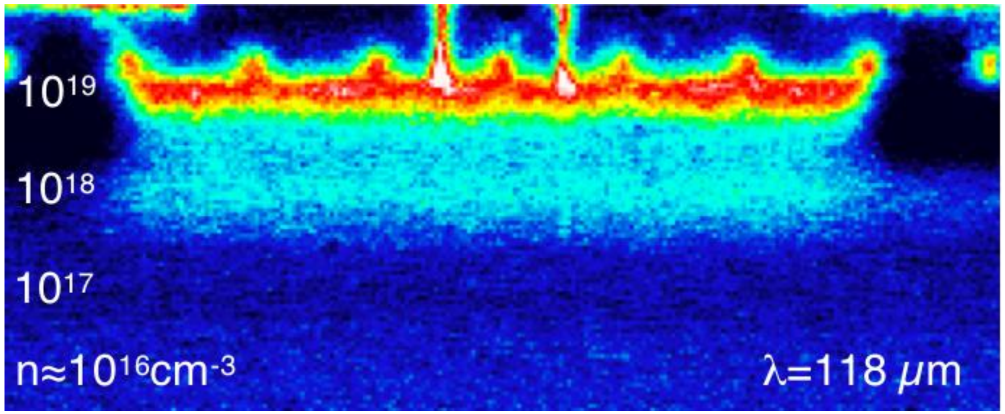


test structure containing transistors of 65 nm - technology

Topography

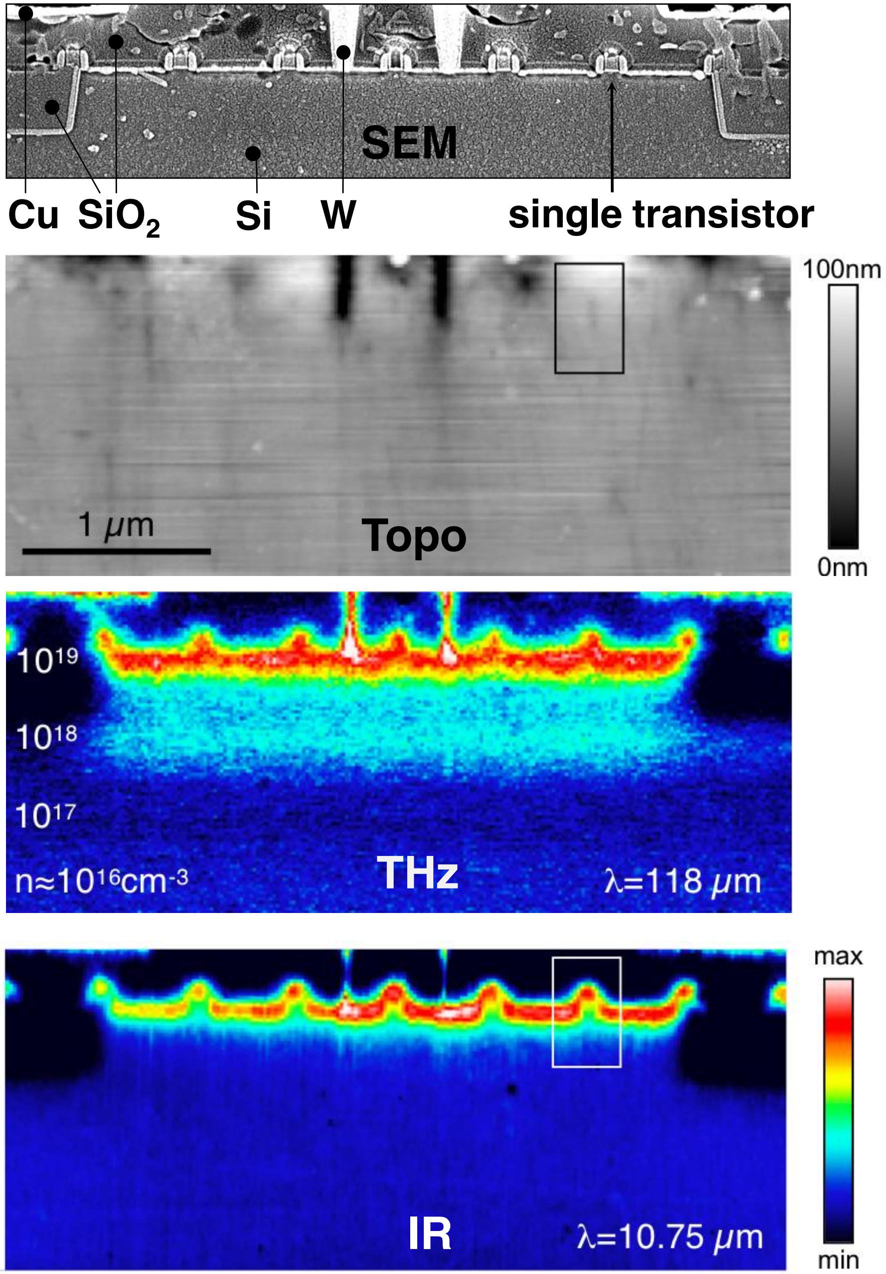


THz image



THz image exhibits **material and free-carrier contrast**

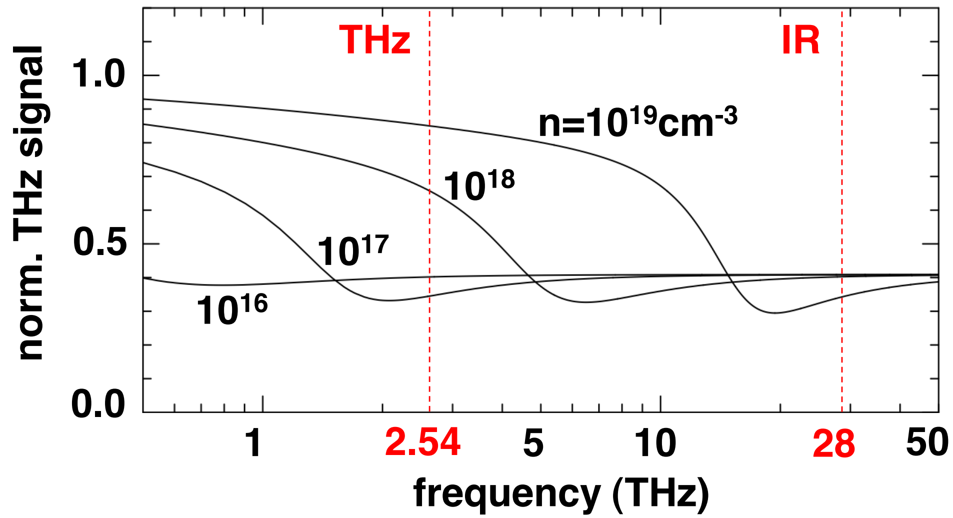
THz s-SNOM can map free carriers in semiconductor devices



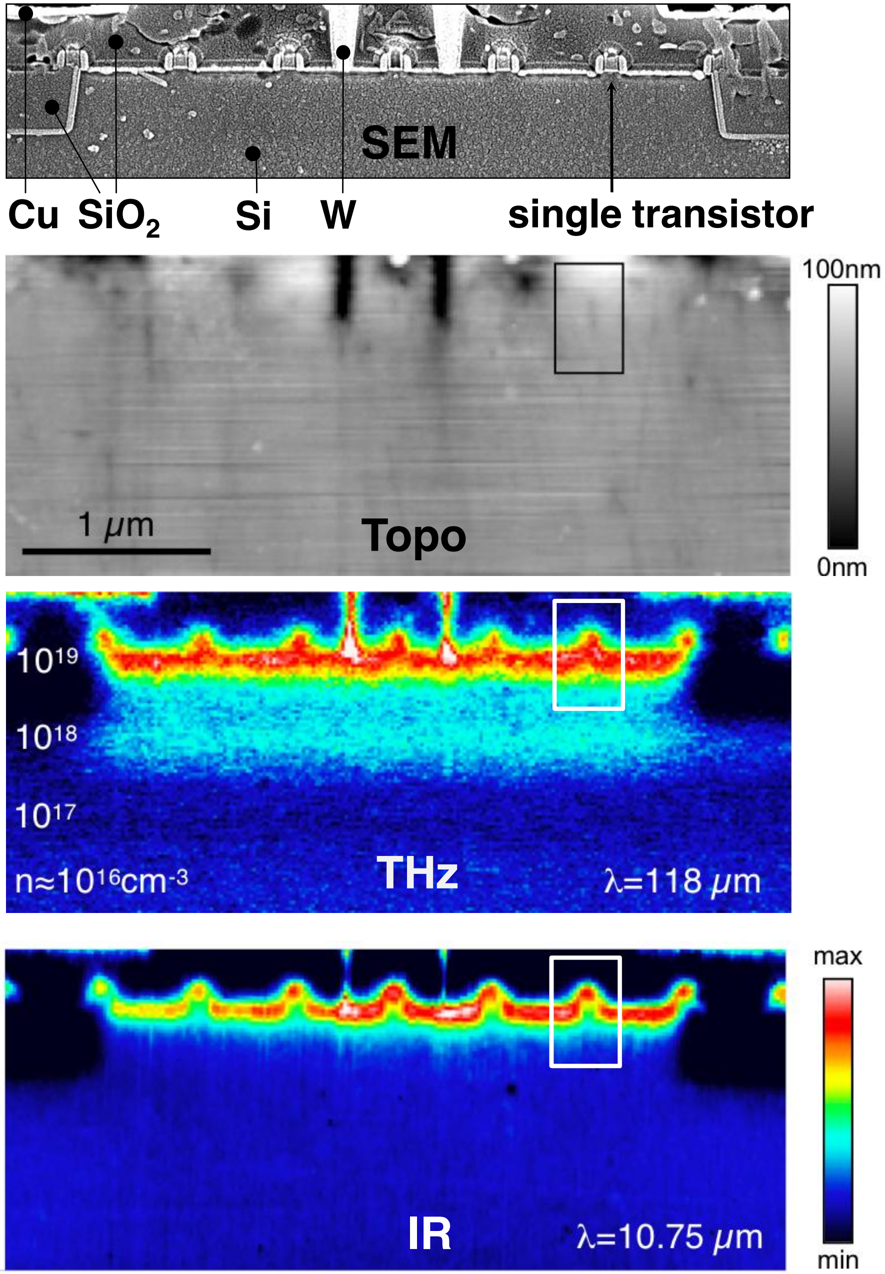
For doped semiconductors ε(ω) depends on concentration of free carriers:

$$\varepsilon(\omega) = \varepsilon_\infty \left(1 - \frac{\omega_P^2}{\omega^2 + i\gamma\omega}\right) \quad \text{with } \omega_P^2 = \frac{n\, e^2}{\varepsilon_0 \varepsilon_\infty m \cdot m_0}$$

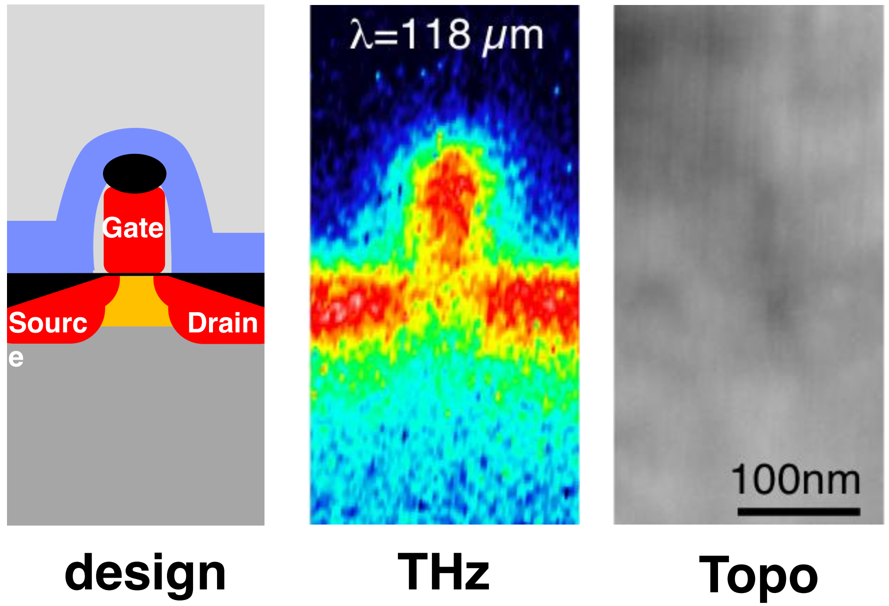
Dipole model explains free-carrier contrast



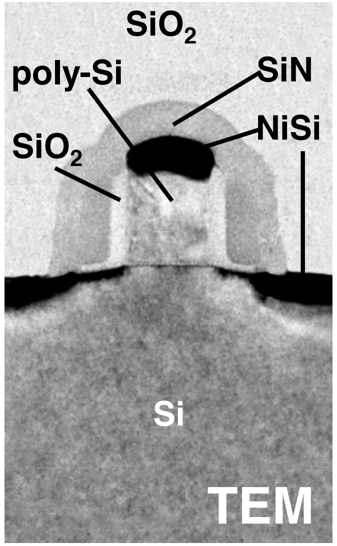
THz s-SNOM resolves source, drain and gate of single transistors

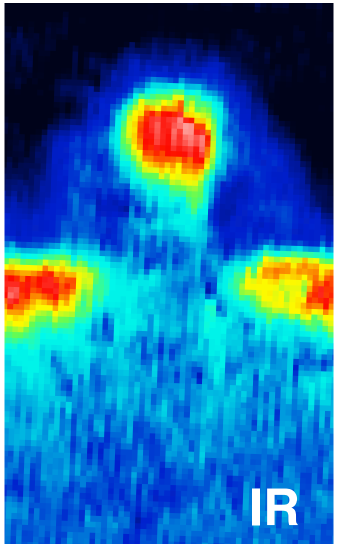


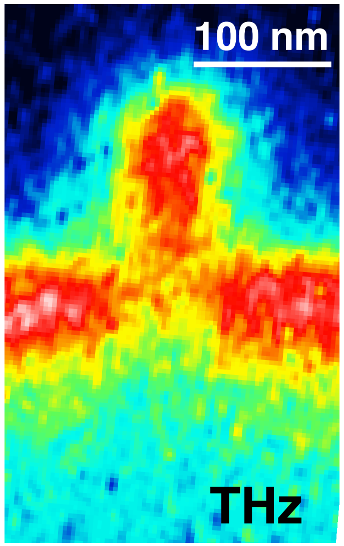
Single 65 nm - transistor



THz s-SNOM maps free carriers with nanometric resolution



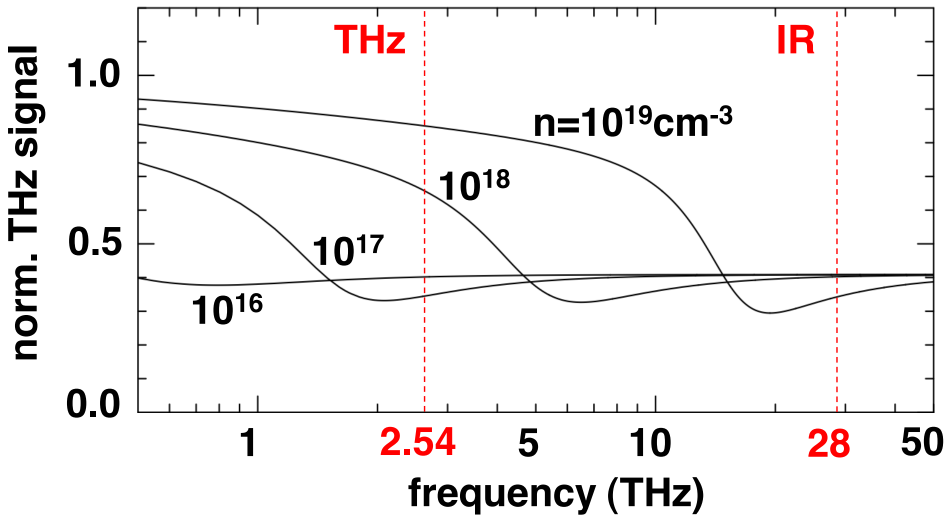




For doped semiconductors ε(ω) depends on concentration of free carriers:

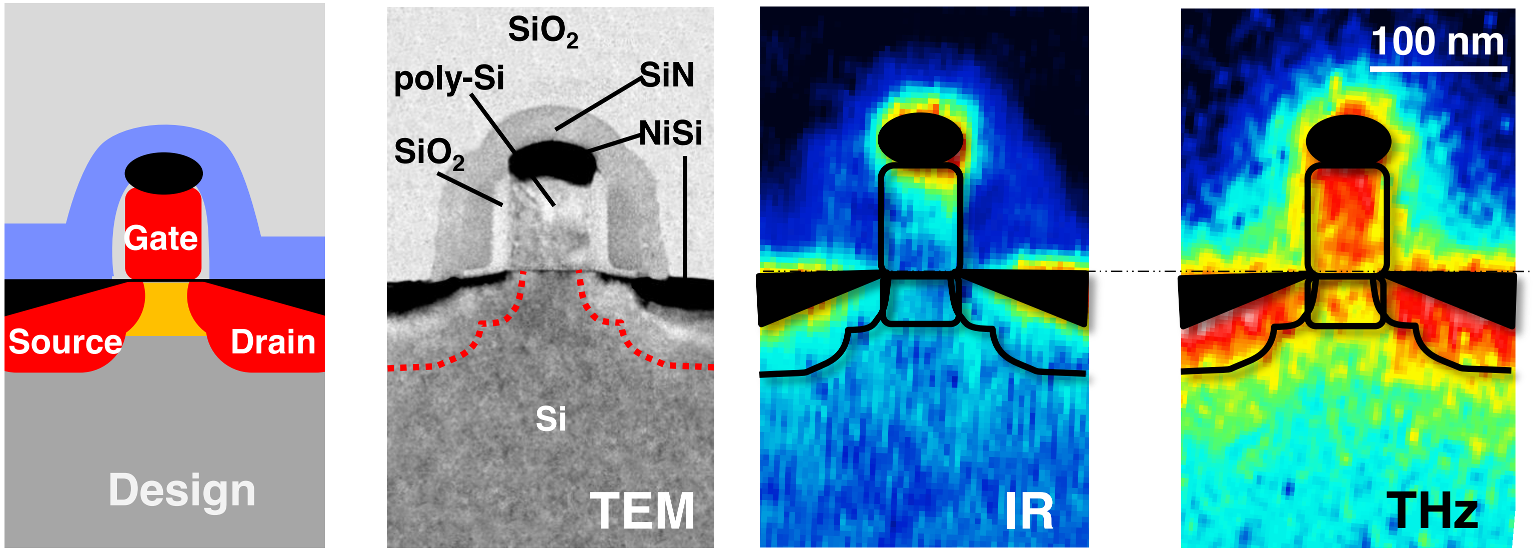
$$\varepsilon(\omega) = \varepsilon_\infty \left(1 - \frac{\omega_P^2}{\omega^2 + i\gamma\omega}\right) \quad \text{with } \omega_P^2 = \frac{n\, e^2}{\varepsilon_0 \varepsilon_\infty m \cdot m_0}$$

Dipole model explains free-carrier contrast



A. Huber et al. Nano Lett. 8, 3766 (2008)

THz s-SNOM maps free carriers in single 65 nm-transistor

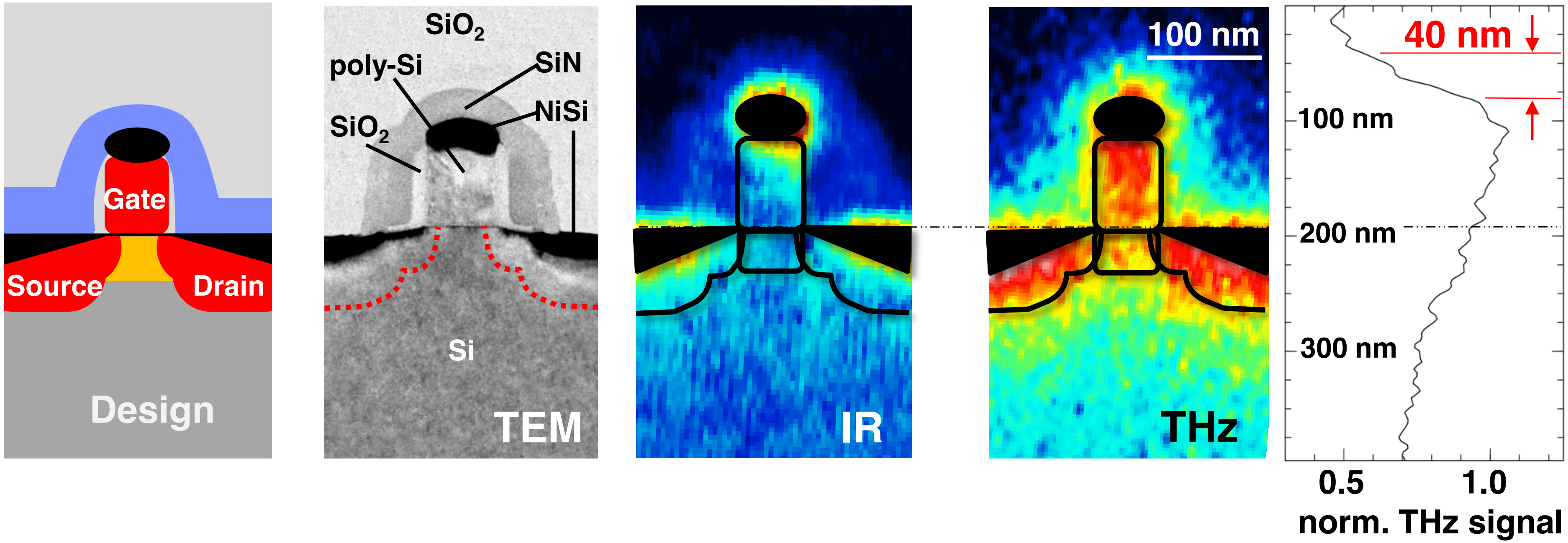


metallic NiSi contacts

highly doped Si, n = 10^{19} cm^{-3}

medium doped Si, n = 10^{18} cm^{-3}

THz s-SNOM achieves a resolution of about 40 nm



⇒ substructure of single 65 nm-transistor can be characterized with THz

⇨ s-SNOM offers nanoscale spatial resolution at THz frequencies

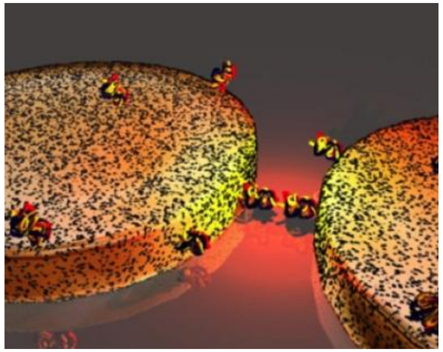
⇨ Achieve 40 nm resolution at 118 μm (= λ/3000)

⇨ THz near-field contrast maps materials and free-carrier concentration

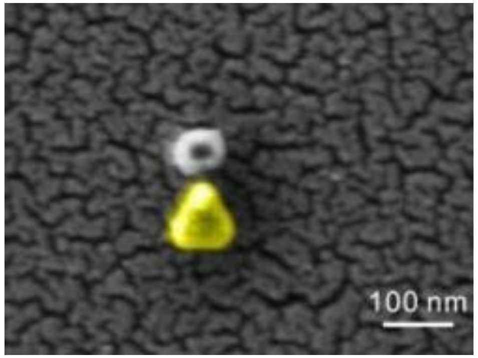
⇨ Promises quantitative and nanoscale resolved mapping of free carriers)

Optical nanoantennas

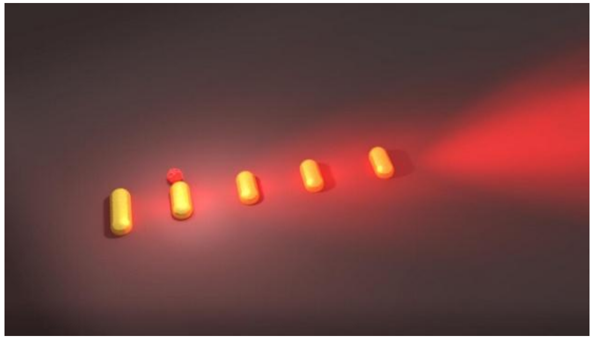
- Applications: biosensing, nonlinear optics / SERS, fluorescence, quantum optics,...



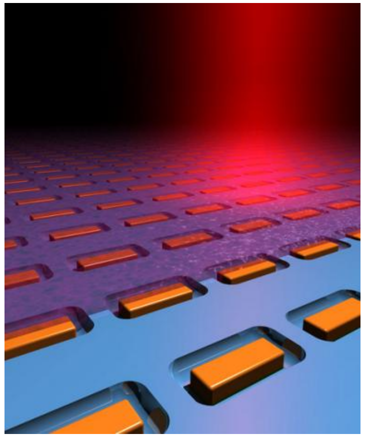
Quidant, ICFO
Antenna-gap sensing



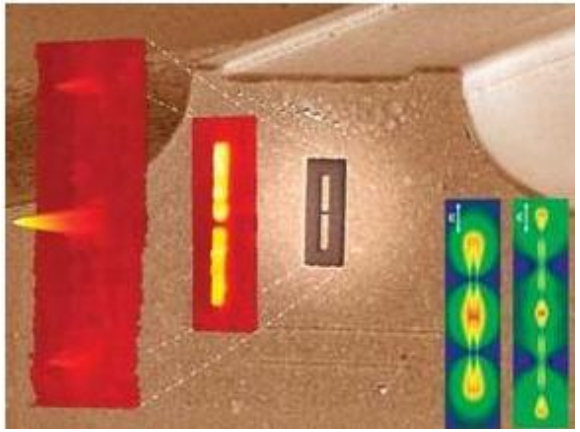
Alivisatos, Giessen
Pd-antenna sensor



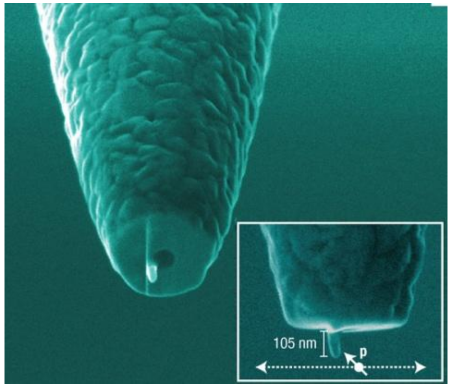
Van Hulst, ICFO - Single molecule, scanning probe



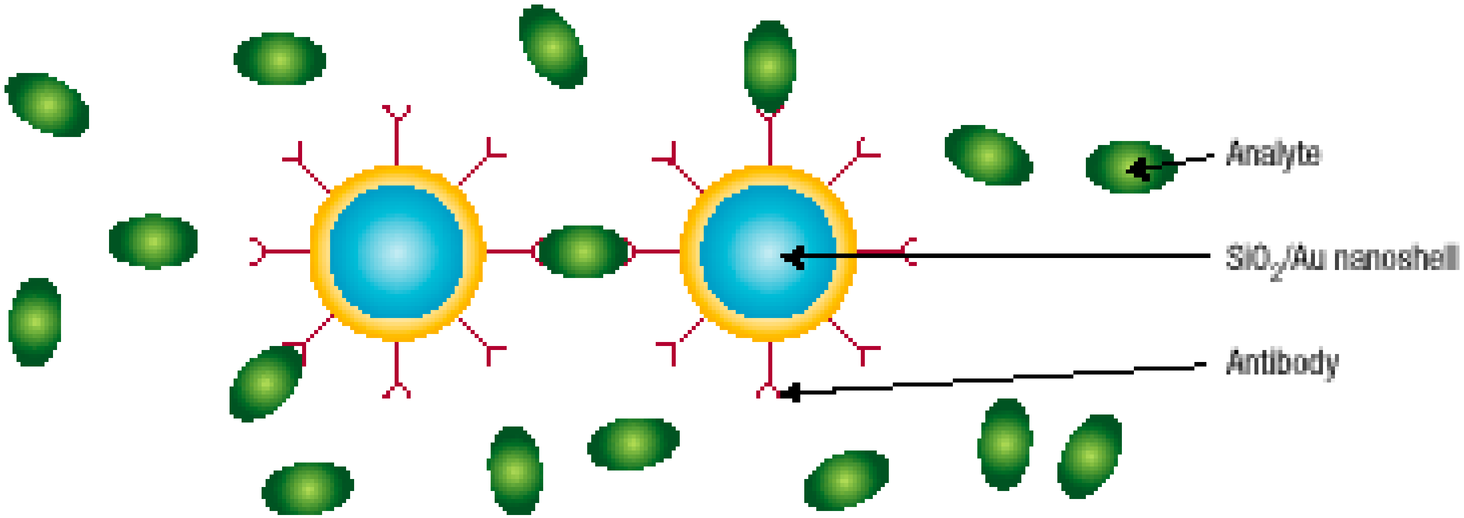
Halas, Nordlander
Plasmonic photodetector



Capasso
Antenna QCL



Nanoantennas as nanoprobes: bio applications



Sensing via coupling

… frequency shift

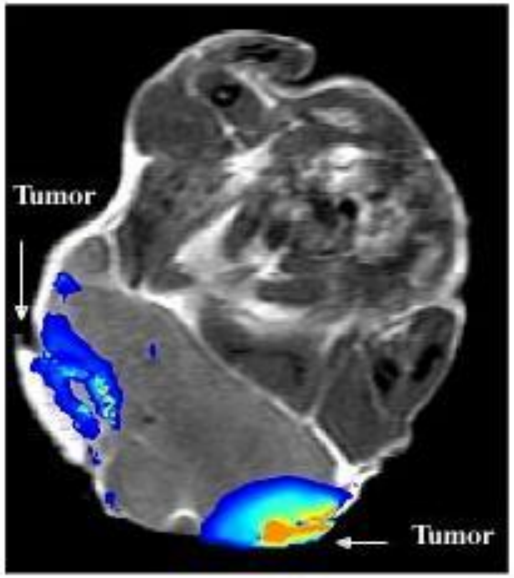
… nanoantenna for scattering

We review this aspect now!

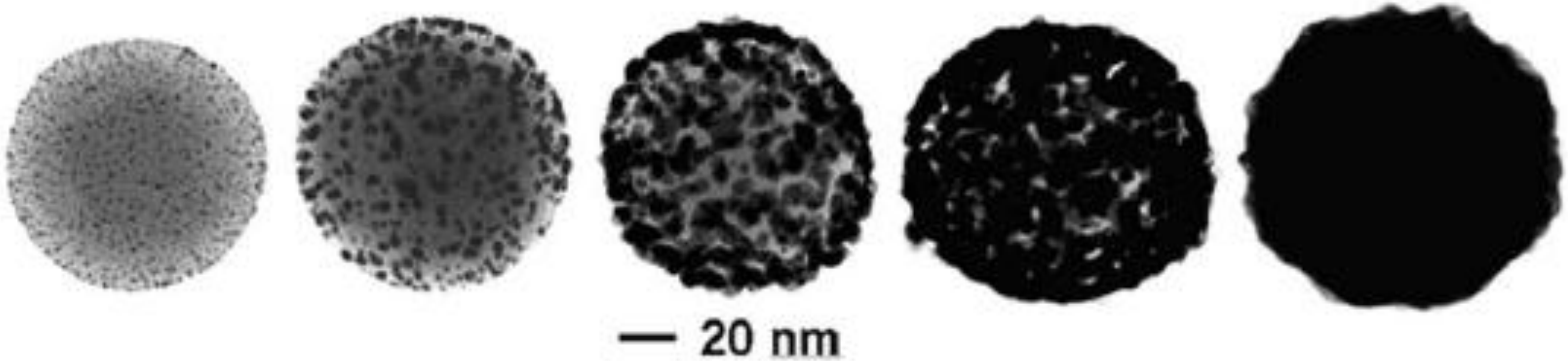
Local heating

… tagging

… nanoantenna for absorption

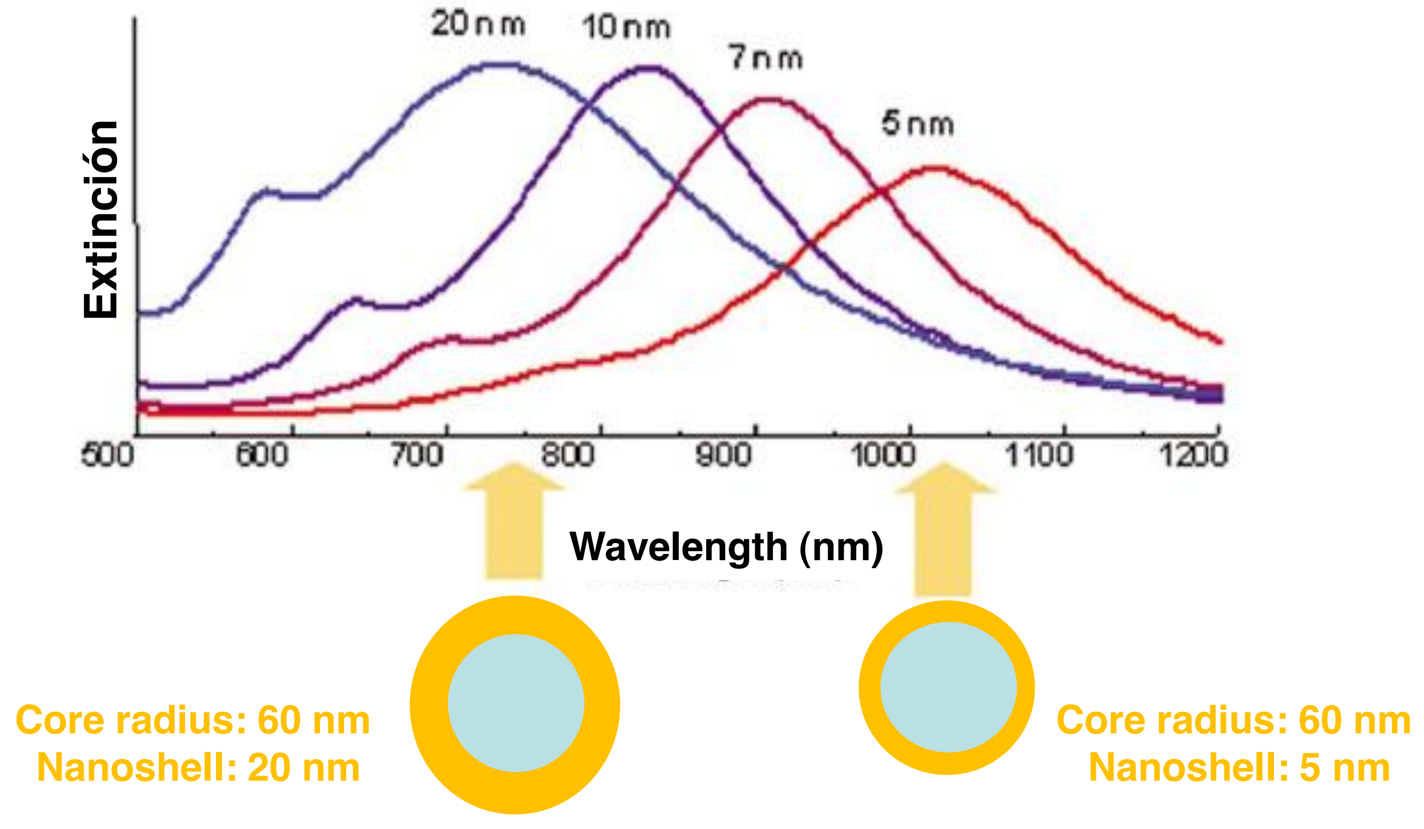


Electrochemical synthesis of metallic nanoshells



N. Halas Group, Rice University, Houston, EEUU.

Visible and infrared radiation absorption by metallic nanoshells



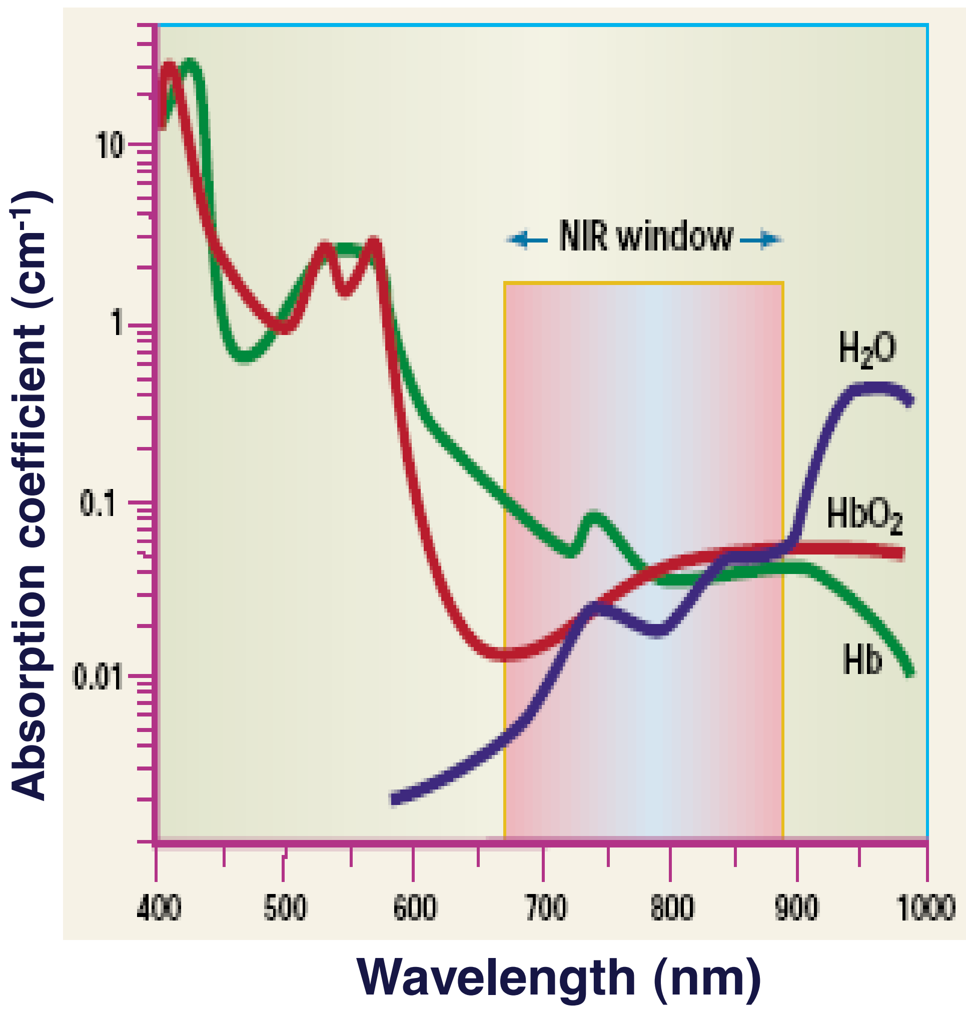
Gold Nanoshells: an ideal nano-bio Interface

Gold nanoshells are completely biocompatible

Small enough to pass through circulatory system
(< 3 μm)

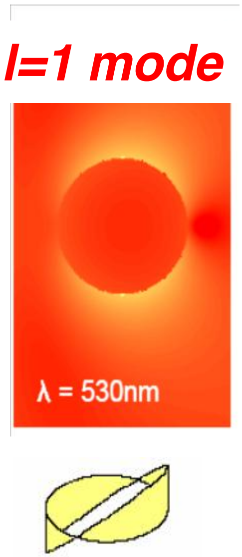
Easily attached to antibodies for specific cellular targeting

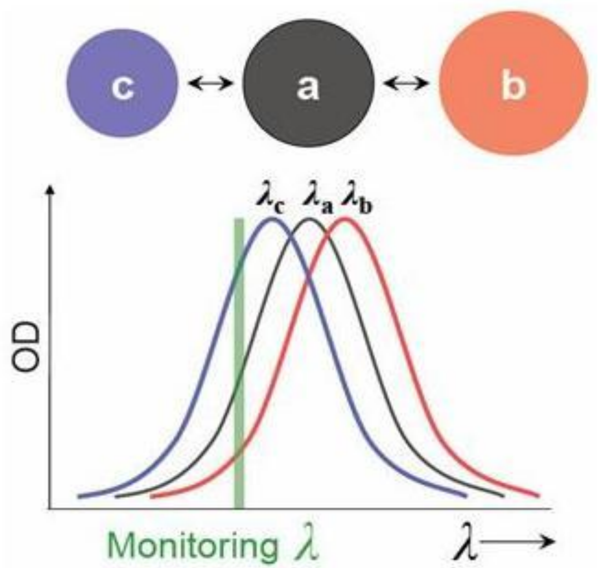
Gold nanoshells are strong absorbers and scatterers of
light in the near infrared,
where light penetrates several inches
into the human body !



Plasmonics for Cancer Therapy

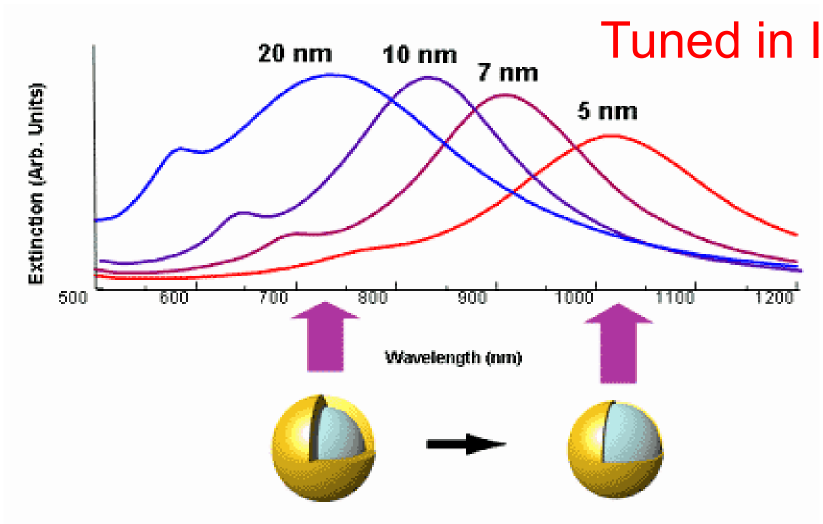
Sphere Localized plasmon (λ=530nm)





Nanoshell plasmons (infrared)

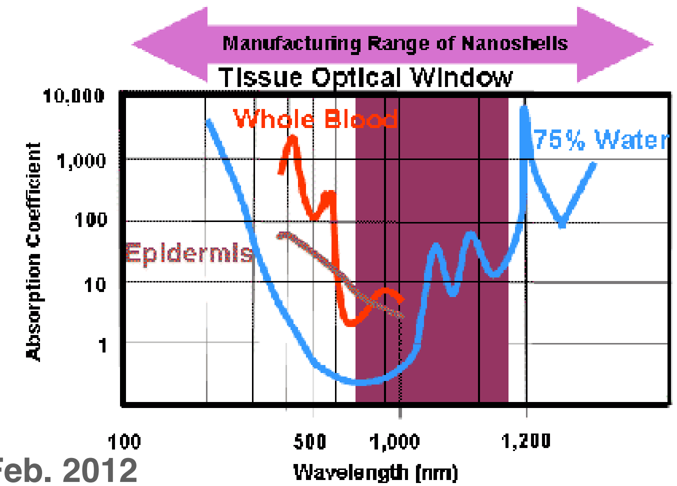
Resonances Tuned in IR



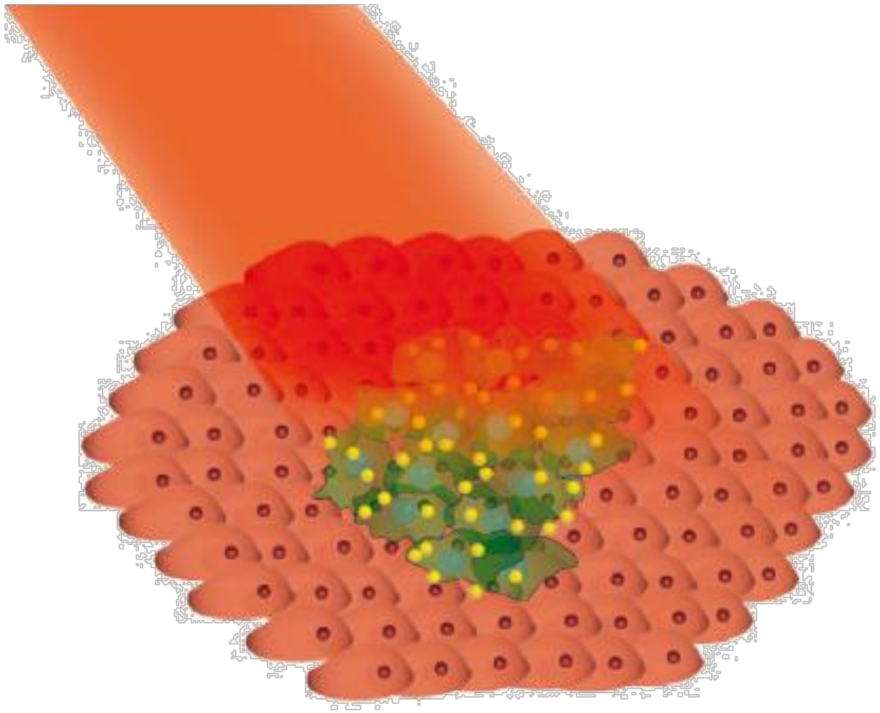
Localized surface plasmons are tuned to the infrared due to the thickness of the shell ➔

Nanoshell functionalization to get attached to cancer cells ➔

IR Absorption ➔ high temperature ➔ cancer cell destruction



Enhanced permeability and retention (EPR) effect

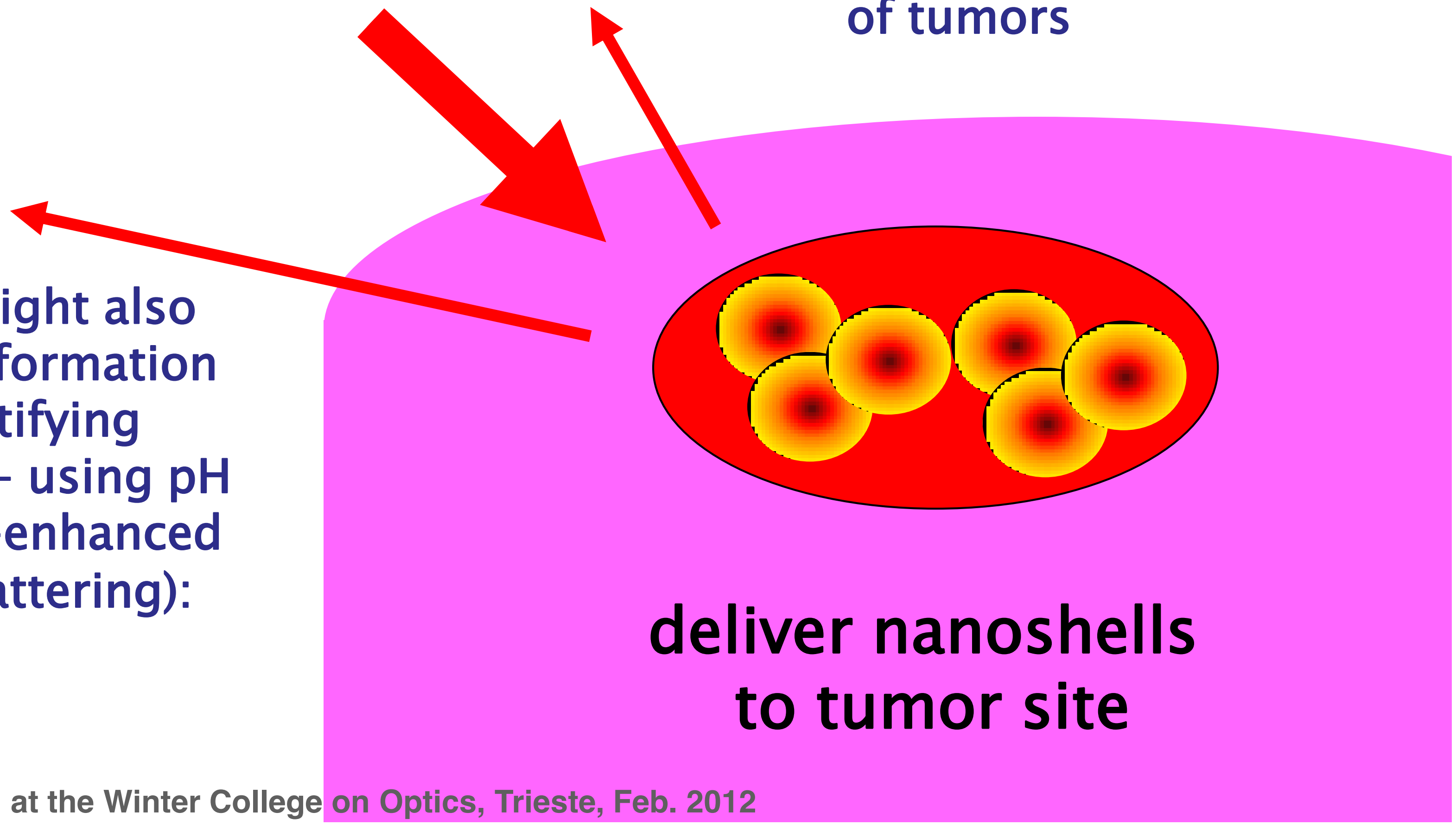


H. Maeda, Adv. Enzyme Regul. 41, 189-207 (2001)

Nanoshell-assisted Seamless Integration of Screening and Therapy: “See and Treat”

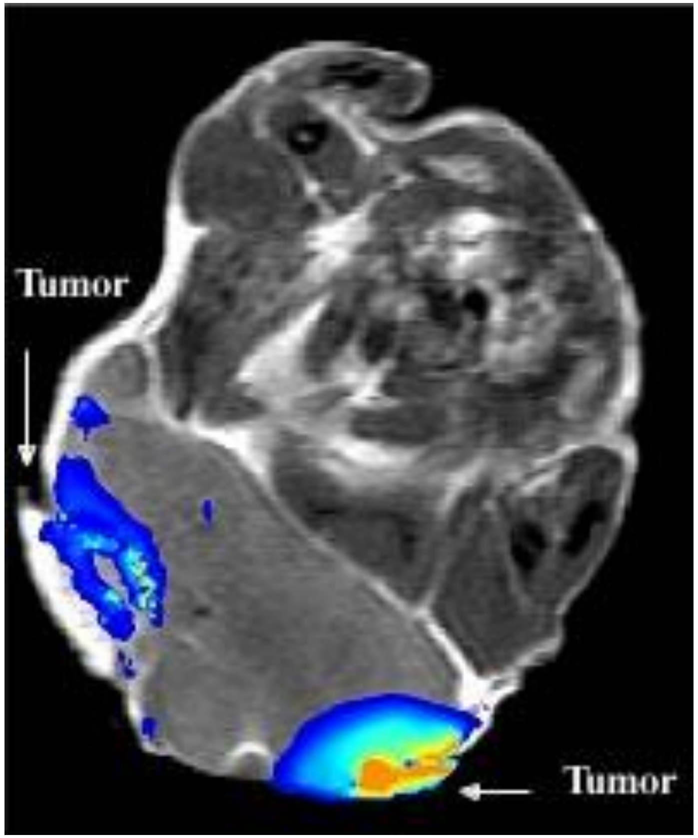
nanoshells provide vivid contrast enhancement, increase image resolution

nanoshells are a photothermal heat source for remote destruction of tumors



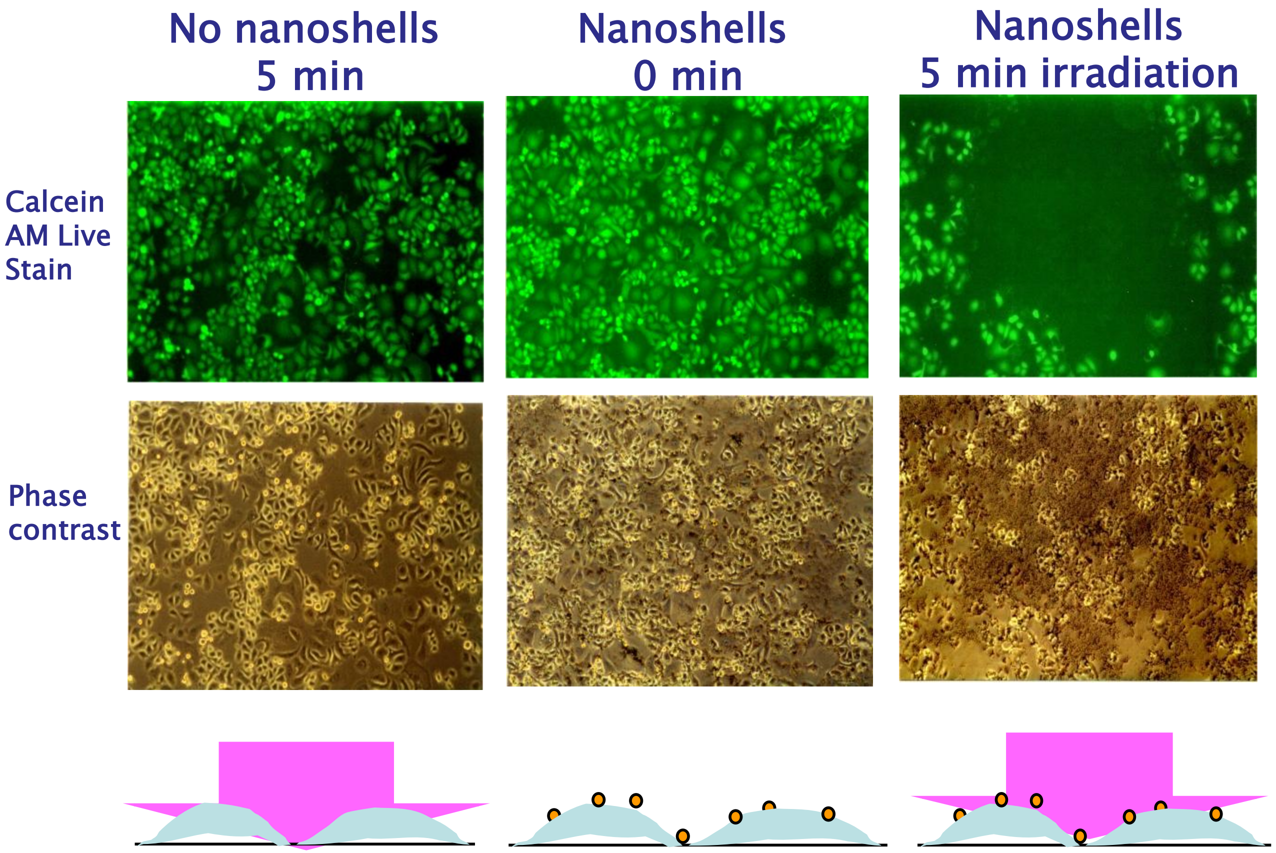
scattered light also provides information for identifying malignancy- using pH (Nanoshell-enhanced Raman Scattering):

Metallic Nanoshells in diagnosis



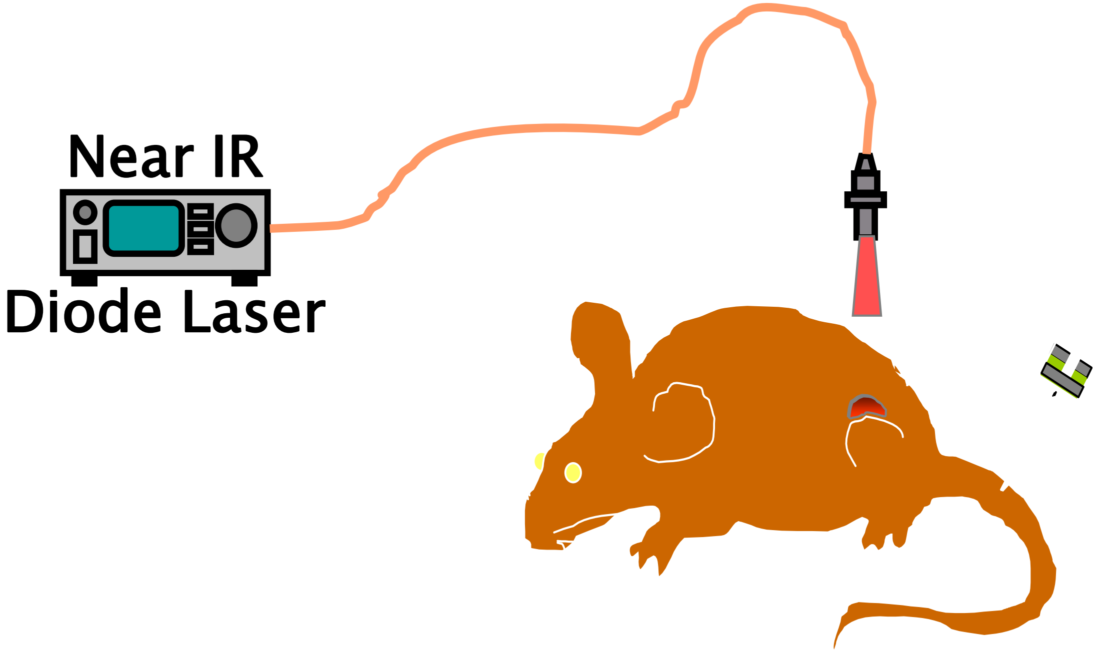
Nanospectra Biosciences Ltd.

Nanoshell-assisted Cancer Therapy



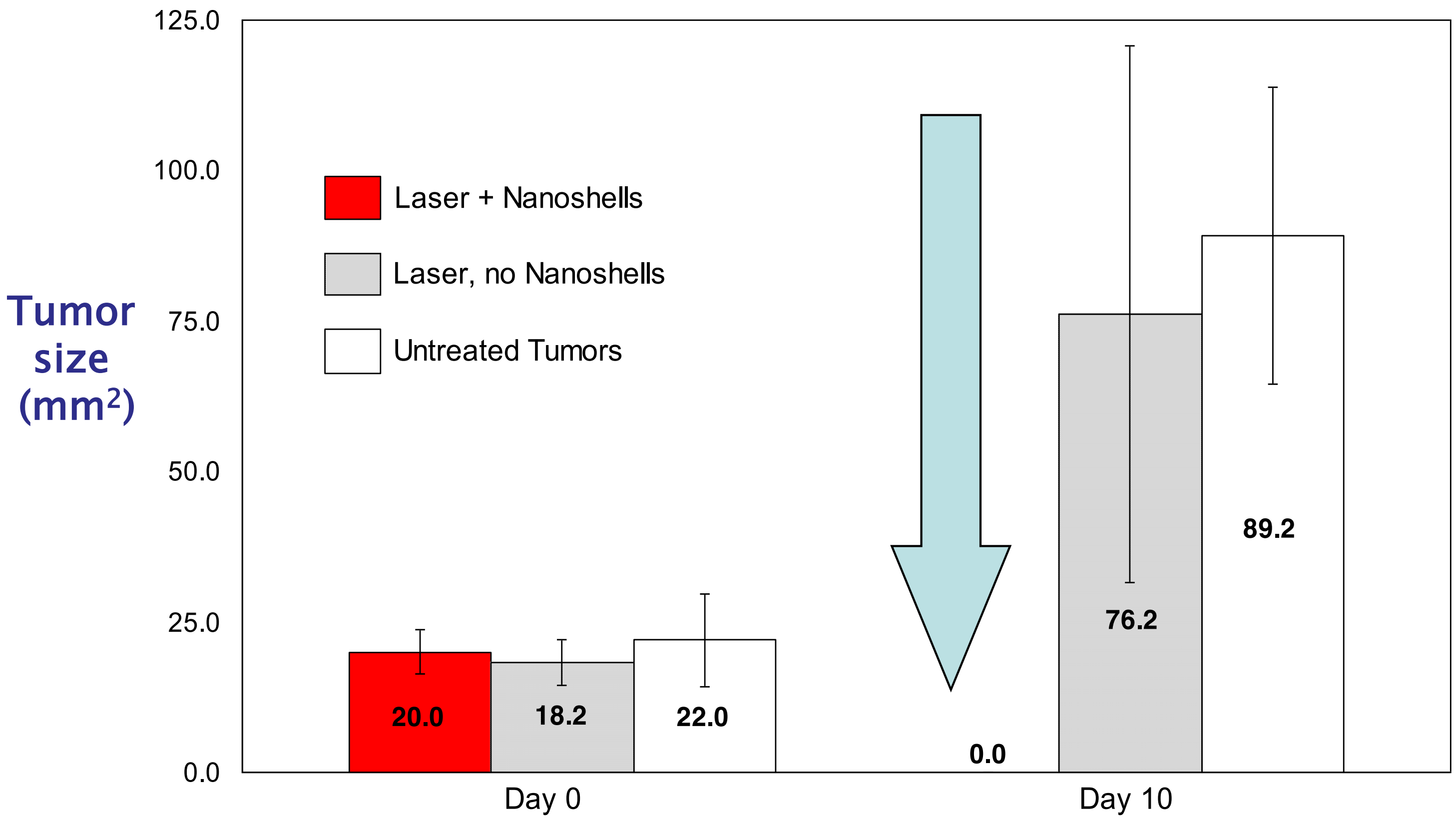
Systemically delivered nanoshell therapy

no targeting used!



- mice innoculated with mouse colon carcinoma cell line
- **Systemically delivered nanoshells via tail vein injection**
- **6 hrs post injection, tumors irradiated with near infrared light through the skin (4 W/cm^2 810 nm diode laser source) for 3 min**
- **Tumor surface temp. monitored using infrared thermometer**
- **Resultant tumor size monitored for up to 2 months**

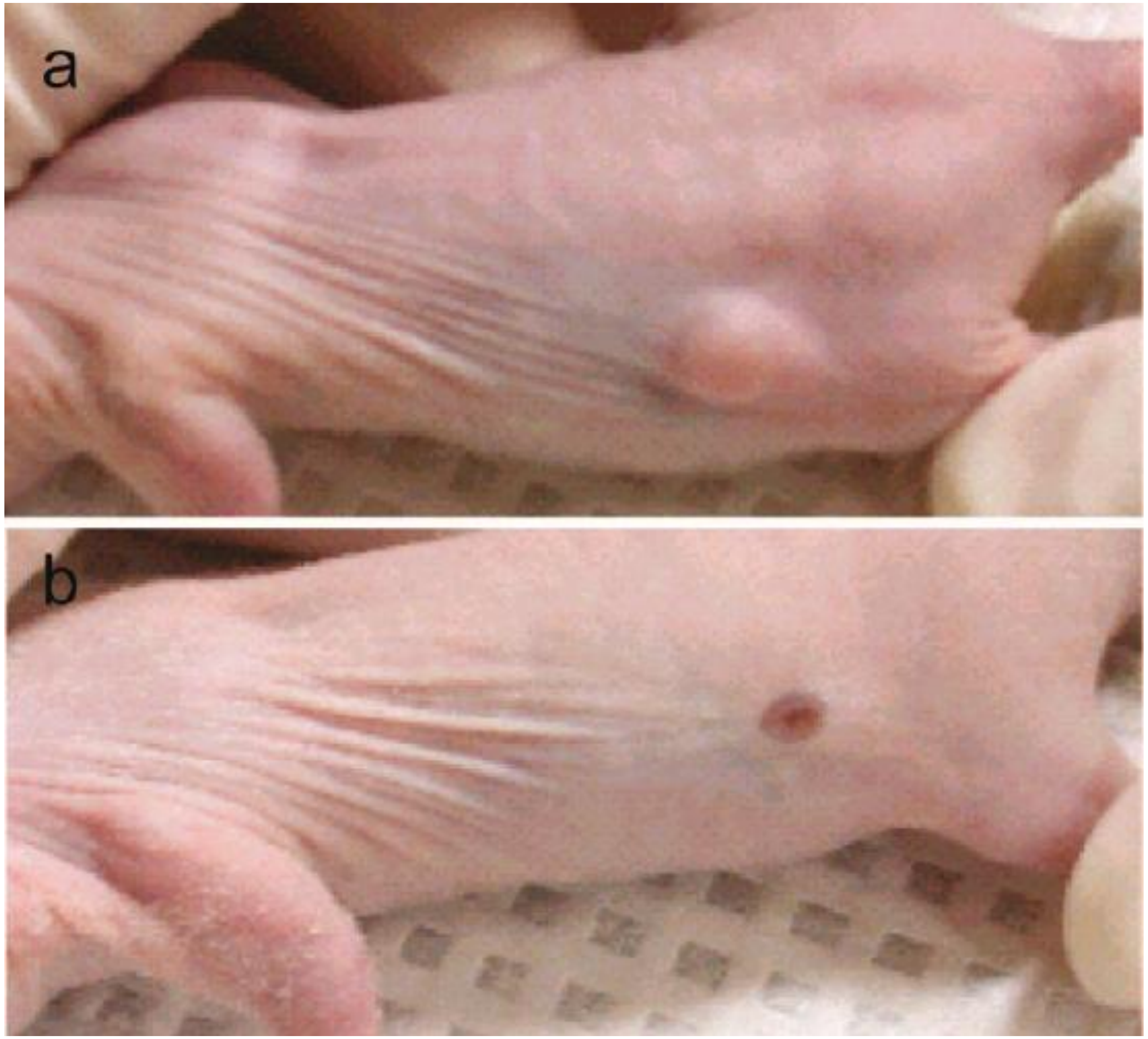
Tumor size before and after therapy



No measurable tumor mass was found in any nanoshell/laser treatments after 10 days

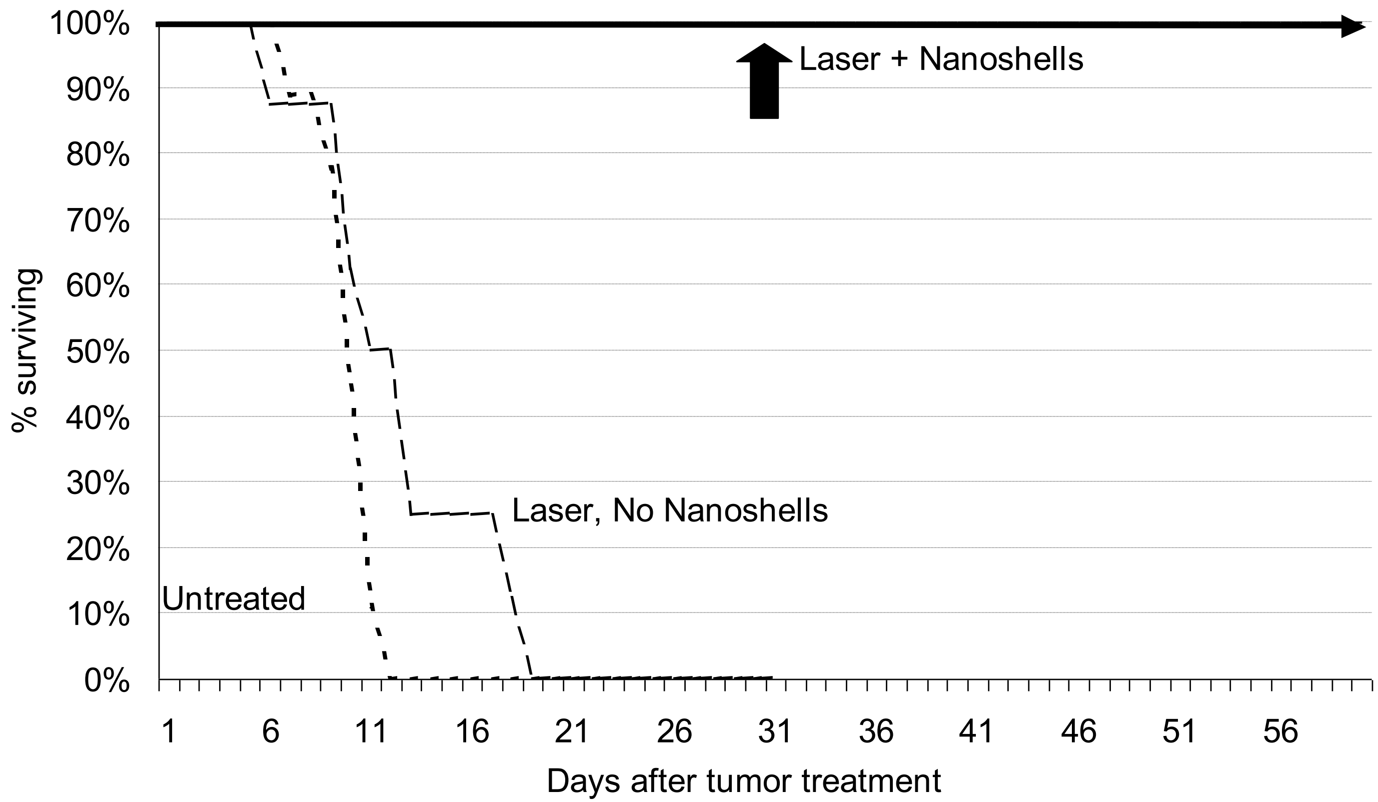
Complete regression of all tumors receiving nanoshell/laser treatments

Treatment in mice



J. M. Stern et al., J. Urol. 179, 748-753 (2008)

Mouse Survival after Therapy



Untreated tumors:

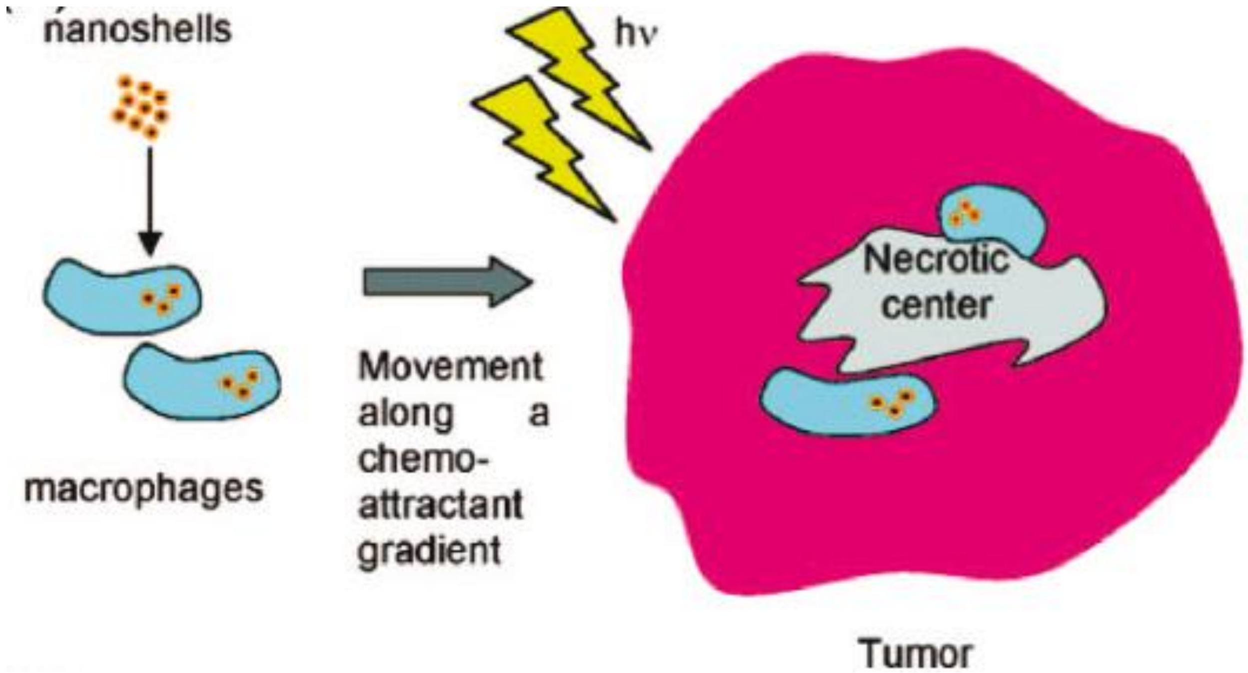
- Mean survival of 10 days

Laser controls:

- Mean survival of 12.5 days

100% of all mice receiving nanoshell/laser therapy survived to end of study (60 days)

Access to hipoxic regions



S. Lal, N. Halas et al., Accounts of Chemical Research. 41, 1842 (2008)

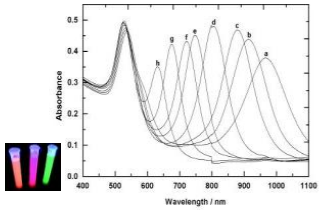
Summary: Nano-optics with localised plasmons

Characteristics

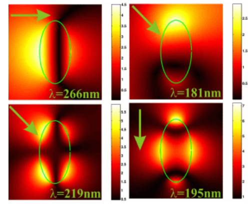
- Confined fields:
  - *Nanooptics*
- Enhanced field:
  - *Lighting rod effect*
- Tunability:
  - *Geometry*
- Coupling:
- Wavelength range:
  - *Visible ➔ Infrared*

Resonances dependence

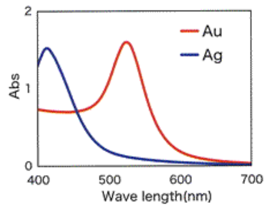
with size



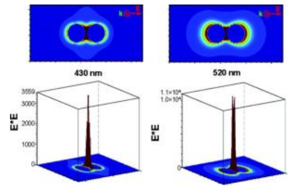
with shape



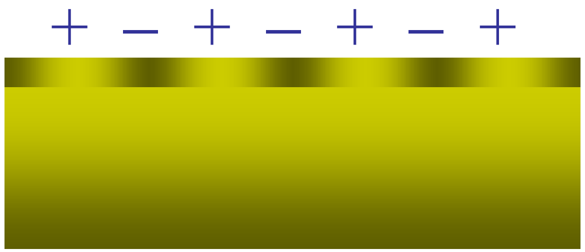
with material

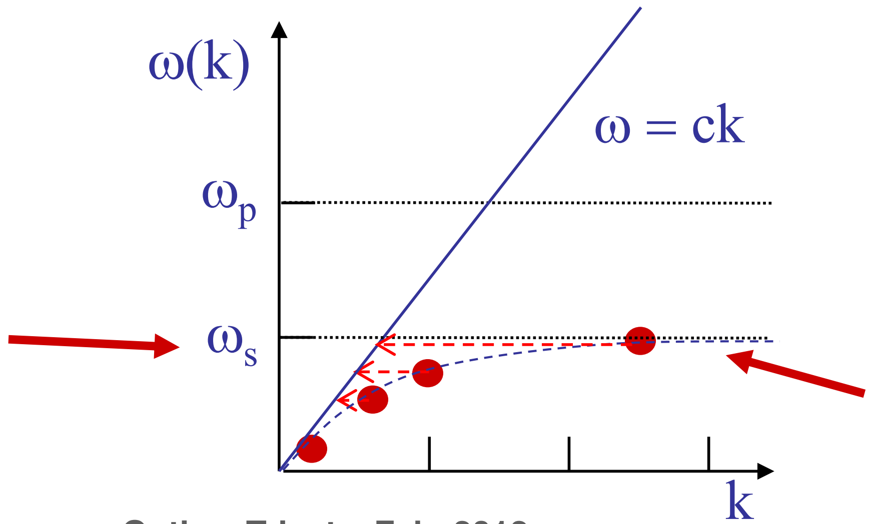


with coupling

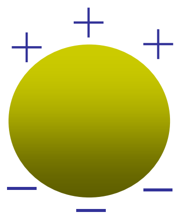


Plasmon polariton





Confined plasmon



Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

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Lecture given by J. Aizpurua at the Winter College on Optics, Trieste, Feb. 2012

Thank you for your attention!

http://cfm.ehu.es/nanophotonics