Plasmonics: optics at the nanoscale

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Harry Atwater

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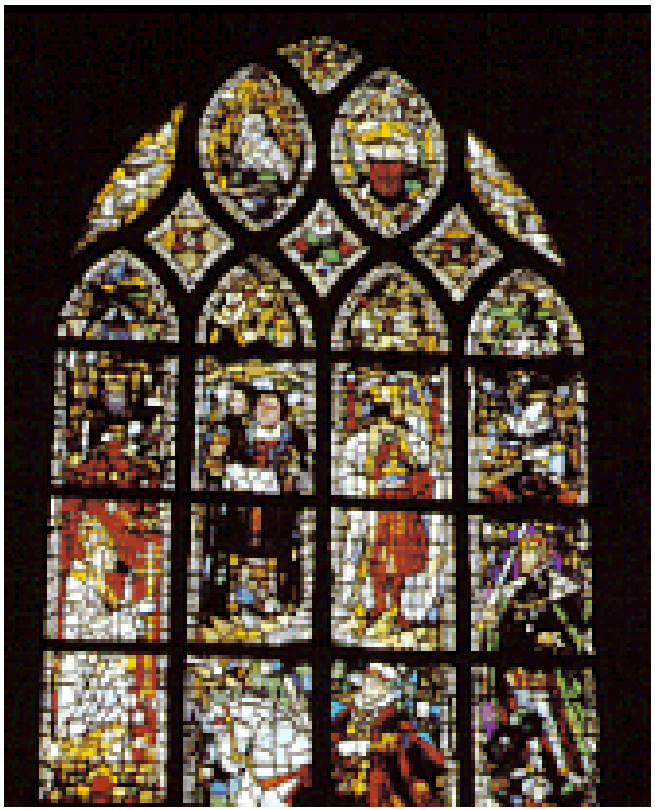
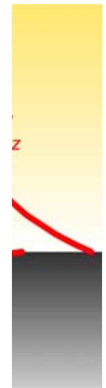
Ruud Schropp

Javier Garcia de Abajo

Surface plasmons:
electromagnetic resonances in the visible



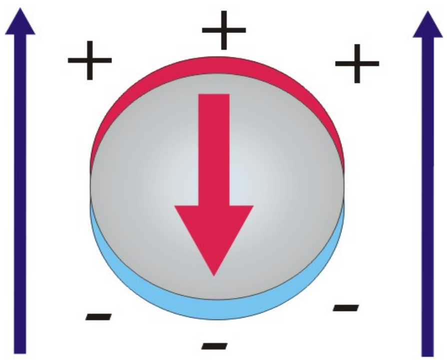
Cu
Ag
Au



aga
p

lielectric
netal

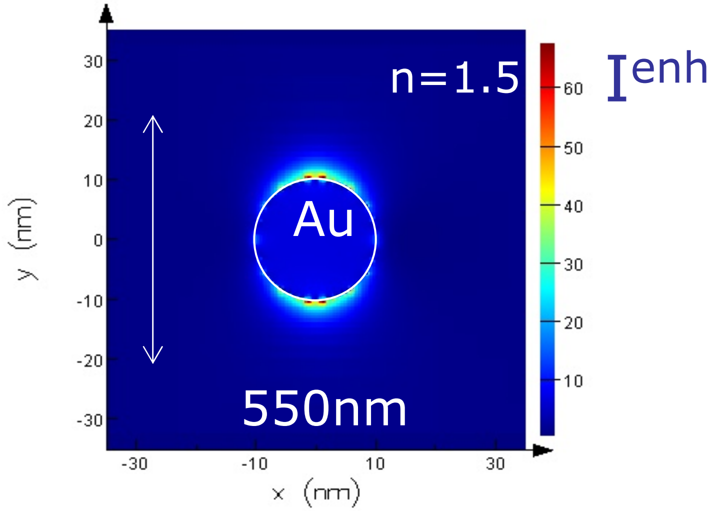
Metal nanoparticle resonance



$$\alpha = 4\pi\varepsilon_0 R^3 \frac{\varepsilon - \varepsilon_m}{\boxed{\varepsilon + 2\varepsilon_m}}$$

dielectric metal

20 nm Au

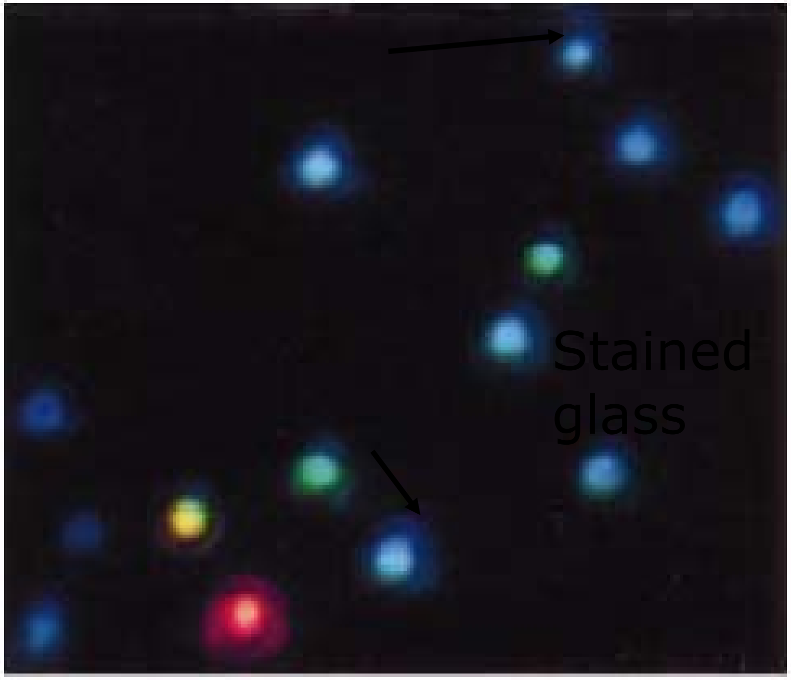


Resonance in visible

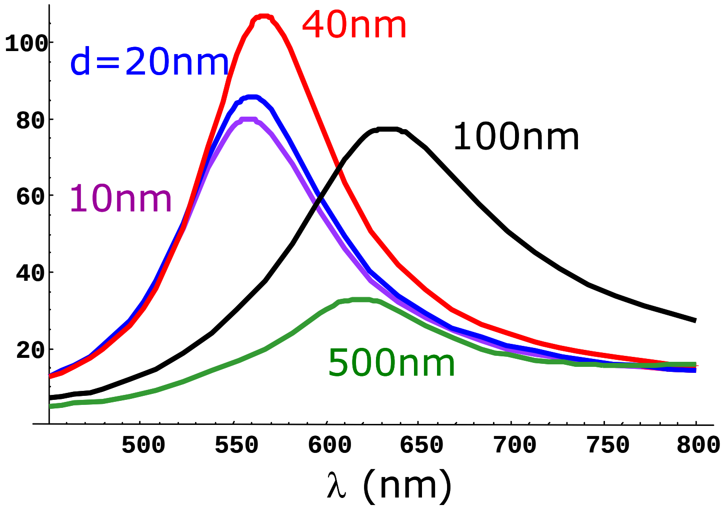
AMOLF FOM

Resonance tunable by particle diameter

Dark field image

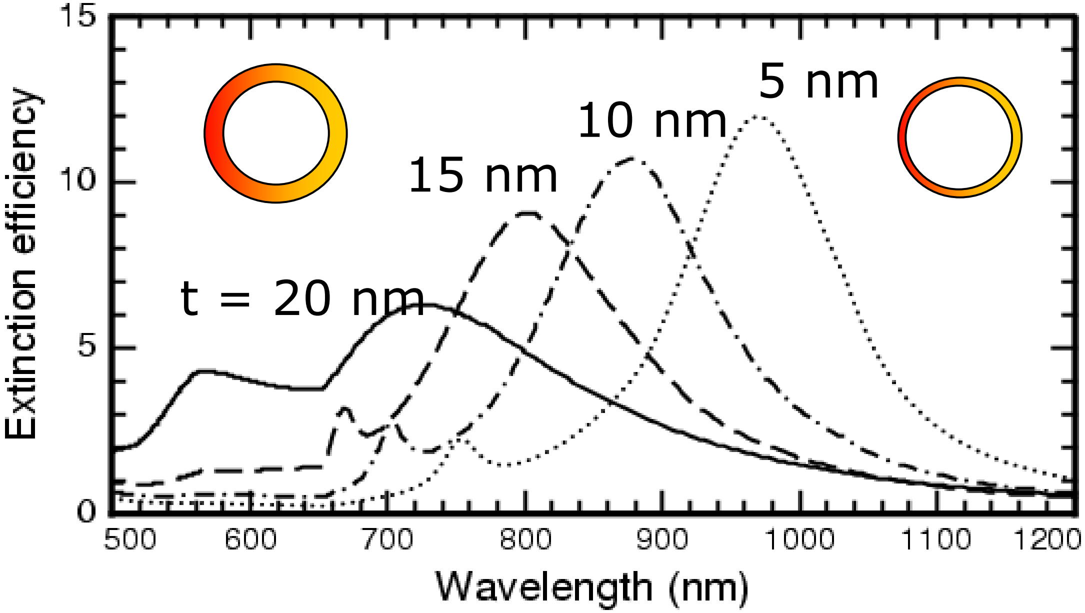


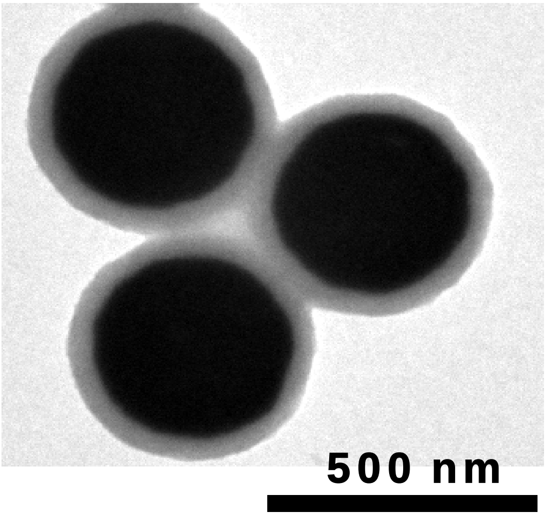
Field enhancement



Metal shell colloids

Plasmon resonance tunable by core and shell dimensions





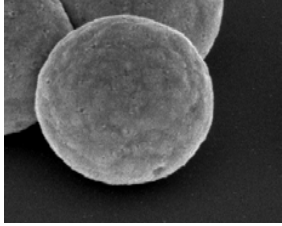
Core radius: 180 nm
Au shell thickness: 46 nm

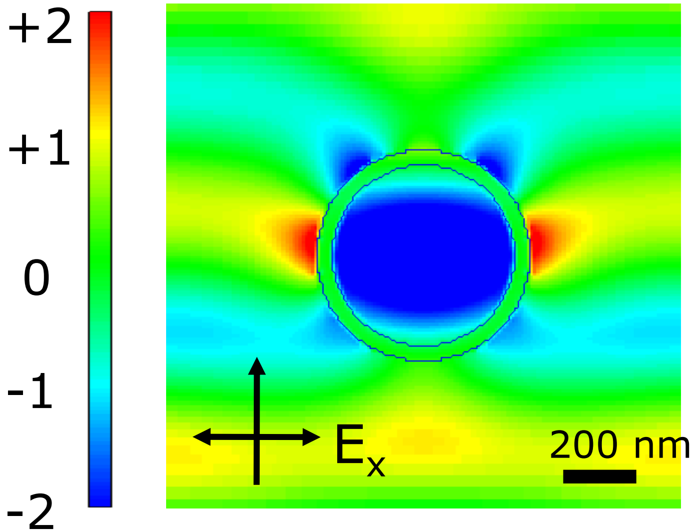
Synthesis Refs:
Halas et al., Xia et al.
Van Blaaderen et al.

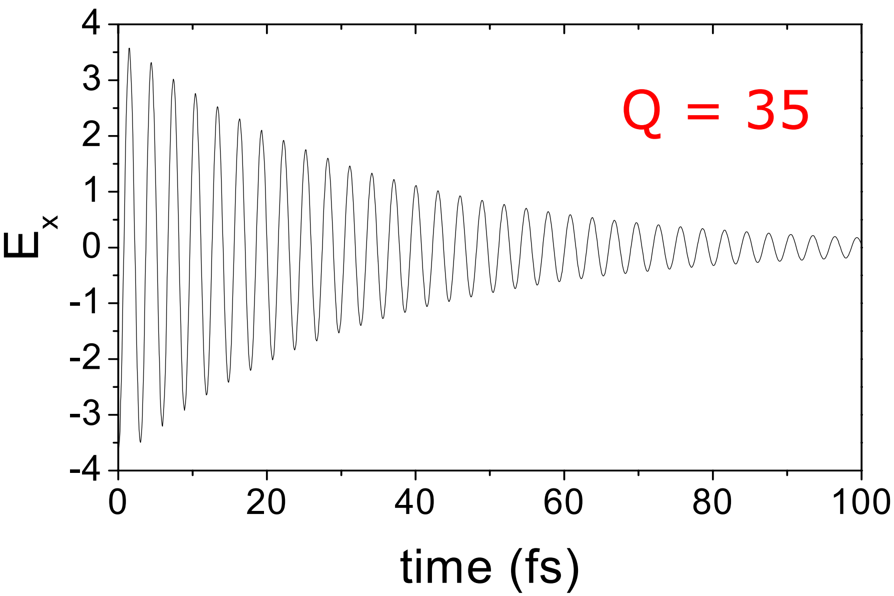
J. Phys. Chem C. **112**, 4146 (2008)

Joan Penninkhof

Gold shell nanocavities

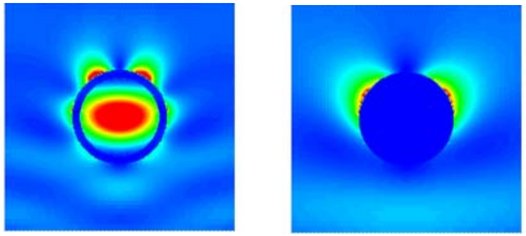




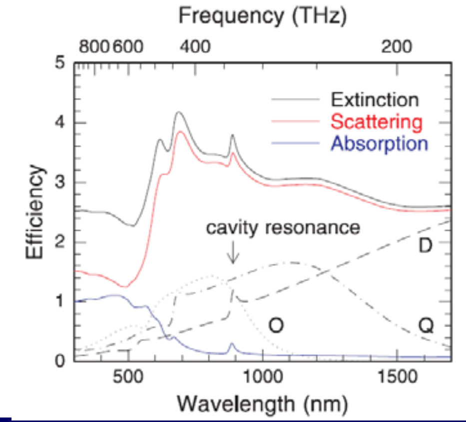


excitation on-resonance
at 335 THz (880 nm)

on-res　　on-res

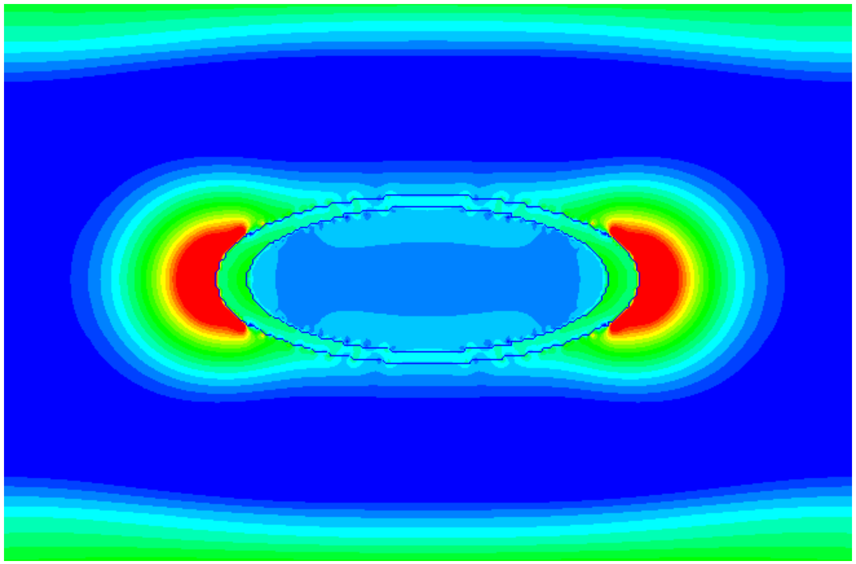


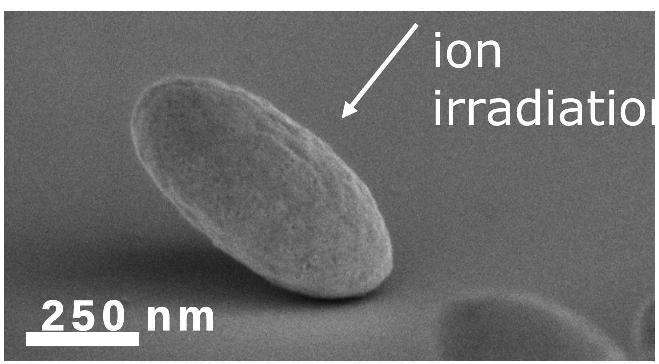
Q > 150
$V = 0.2(\lambda/n)^3$
Purcell factor = 54

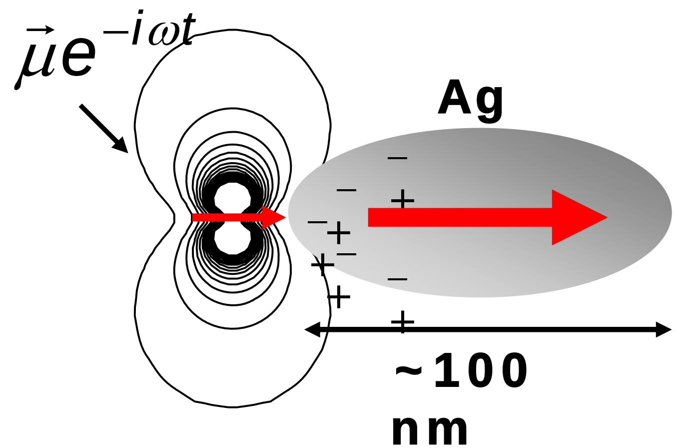


J. Appl. Phys. in press (2008)
Joan Penninkhof, Luke Sweatlock

Shape anisotropy in metal shell cavities

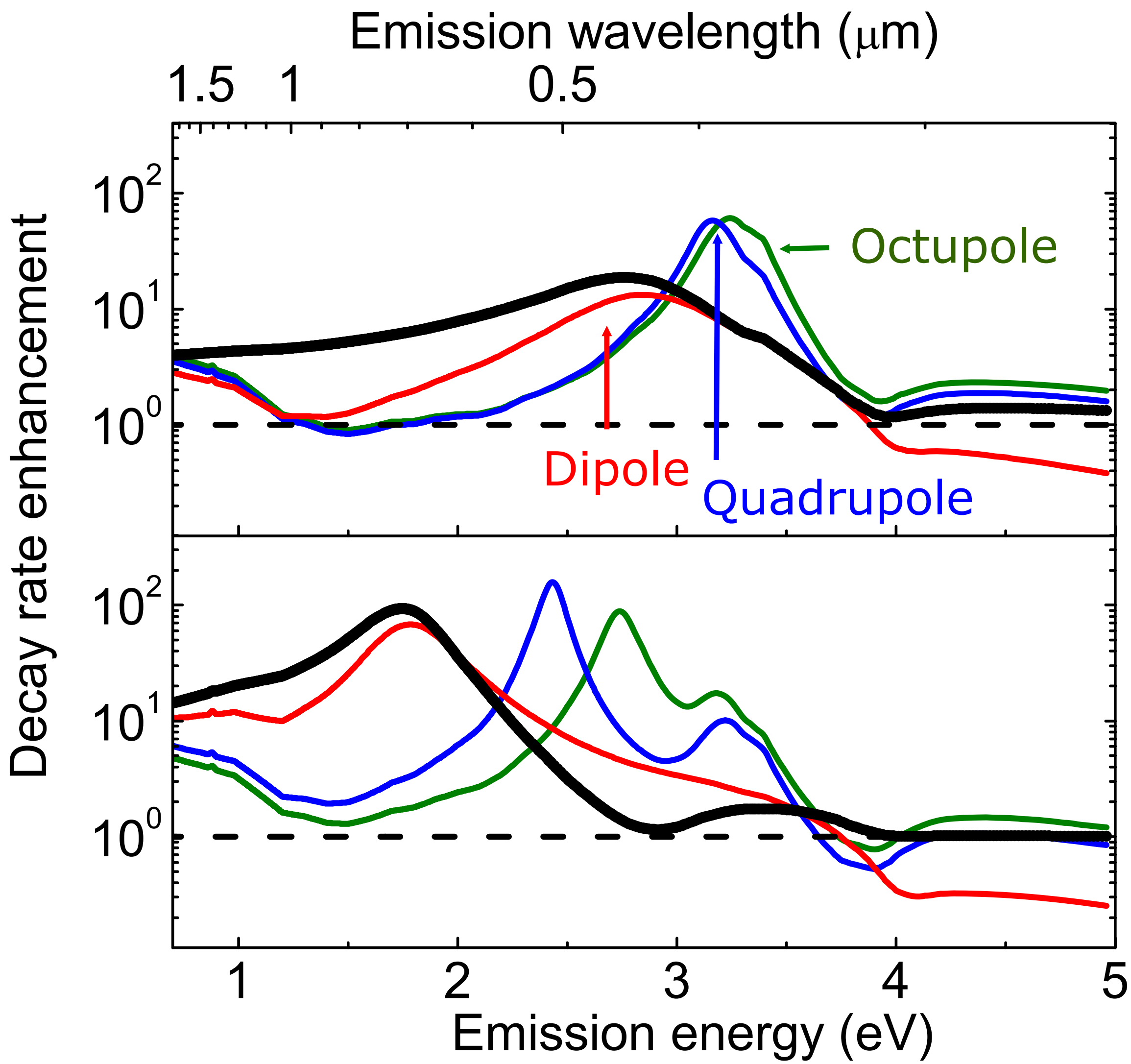


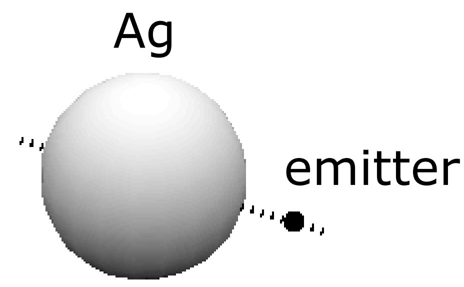




$$P_{dis} = \frac{\omega}{2}\mathrm{Im}\left\{\vec{\mu}^* \cdot \vec{E}\right\}$$

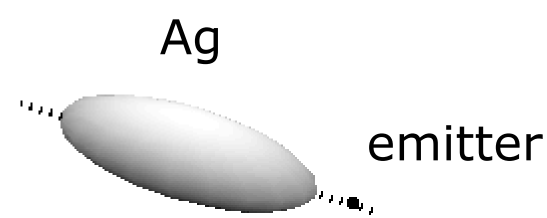
Splitting of radiative and dark modes





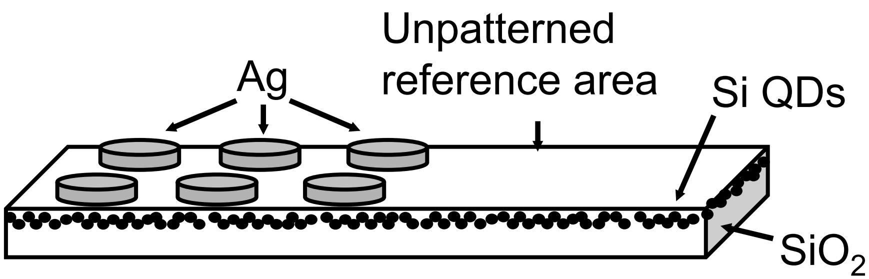
Aspect ratio = 1

Quenching problem solved

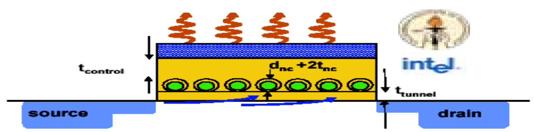


Aspect ratio = 3

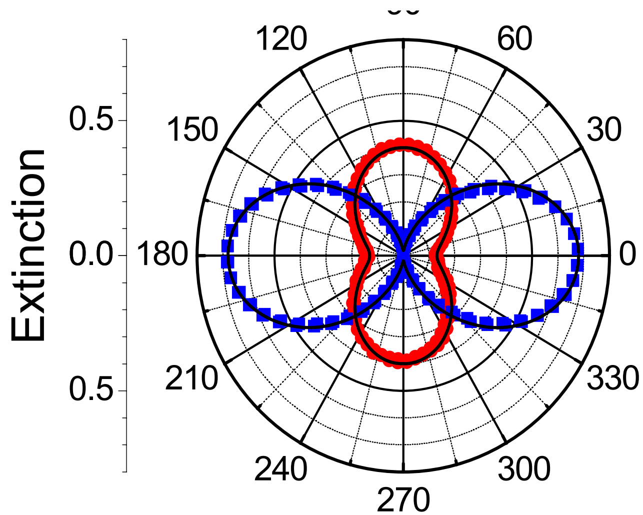
Polarized emission from LEDs: Er, Si QDs

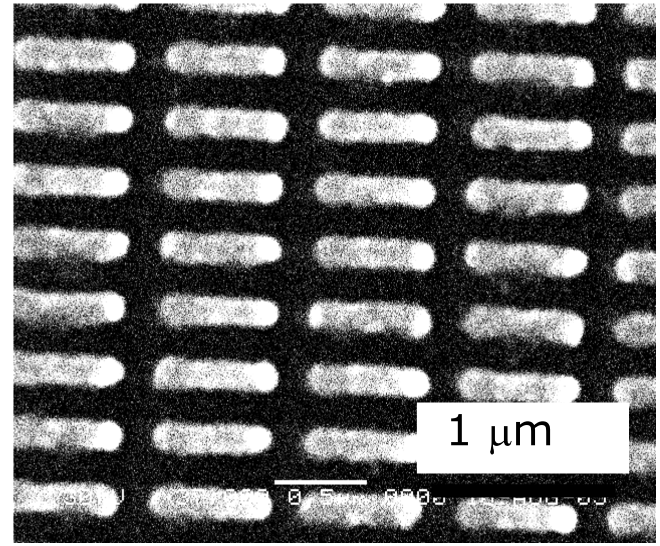


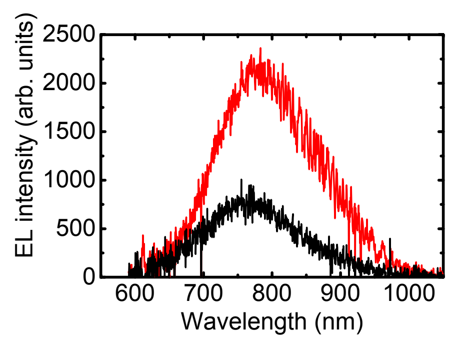
Si QD depth: 10–20 nm

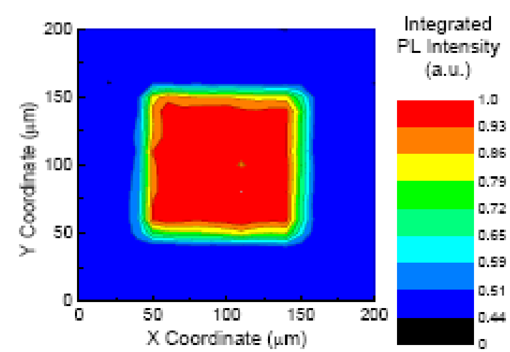


R. Walters et al.,
Nature Materials (2005)





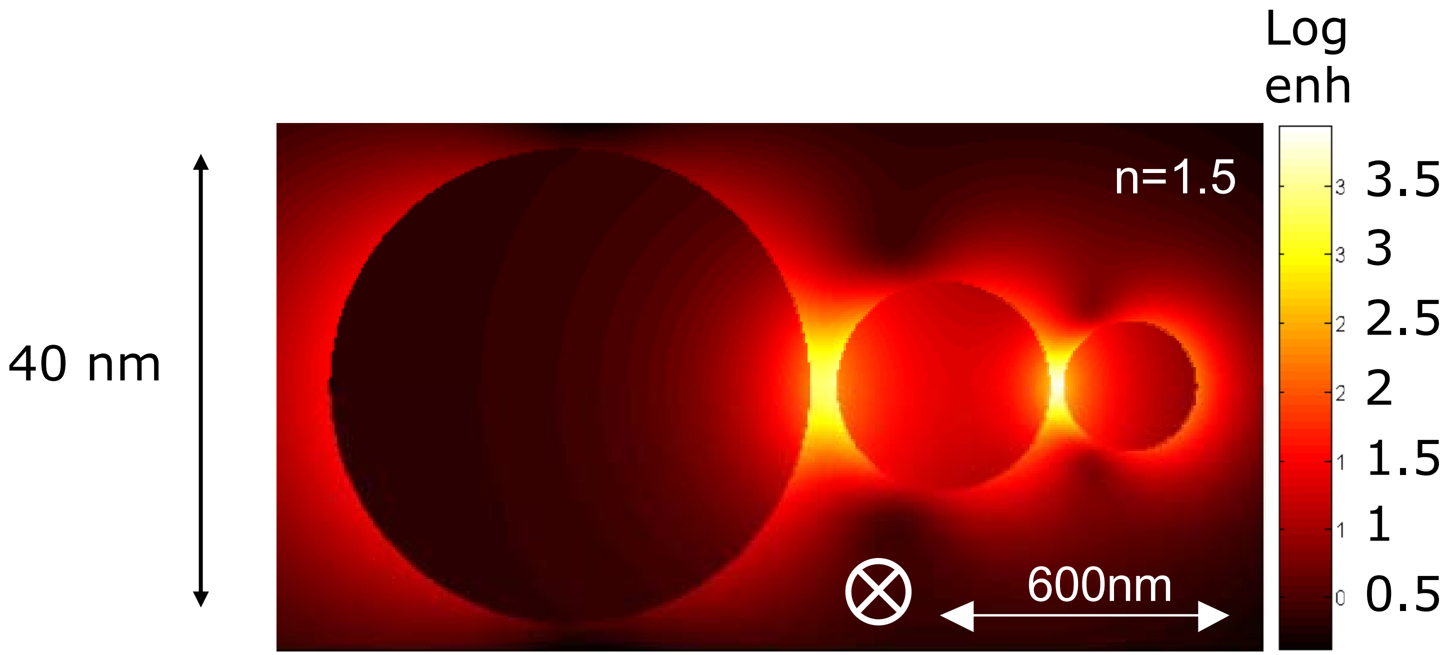




Nano Lett. **6**, 2622 (2006), J. Phys. Chem. C **111**, 13372 (2007)
Appl. Phys. Lett. **89**, 211107 (2006)

Hans Mertens, Julie Biteen

More complex nano-geometries

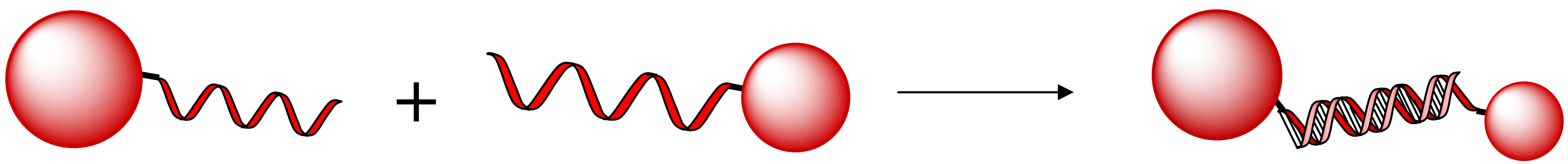


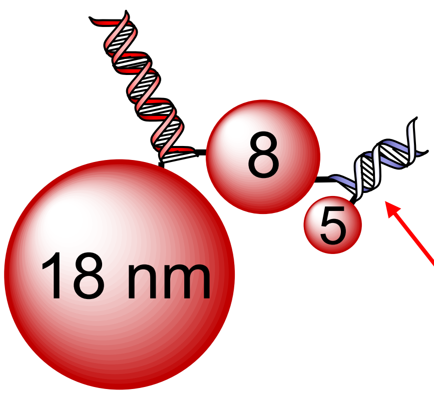
Plasmonic nanolens:
First proposed by Li, Stockman & Bergman, PRL (2003)

JACS **130**, 2750 (2008)

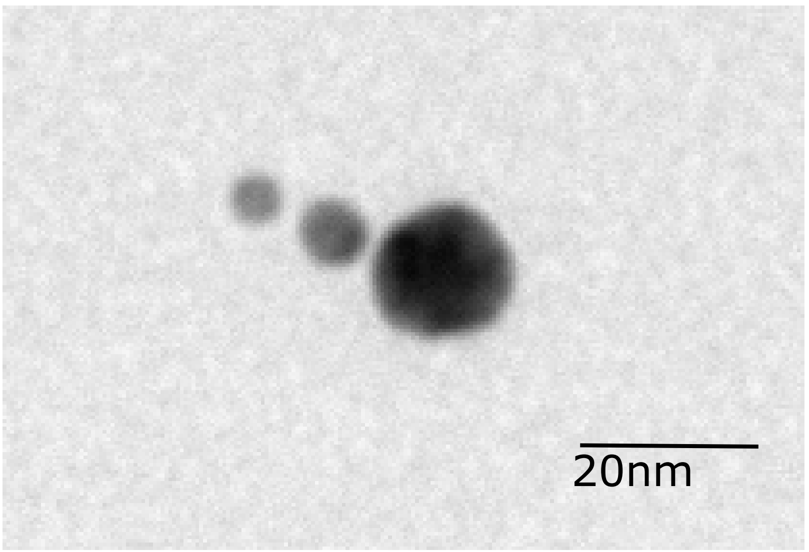
Sébastien Bidault

DNA-templated Au nanospheres





Biomolecule analyte functionalization



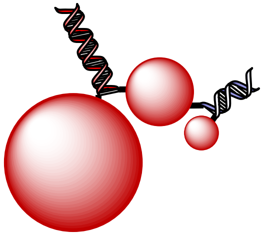
JACS **130**, 2750 (2008)

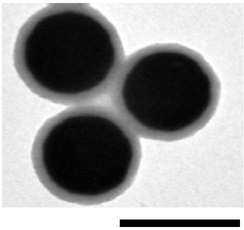
Sébastien Bidault

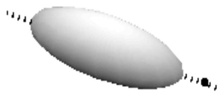
Plasmon tuning range: 400 - > 3000 nm

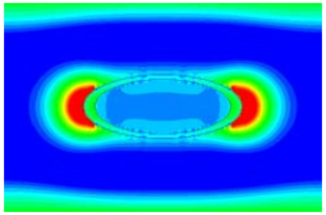
Applications:

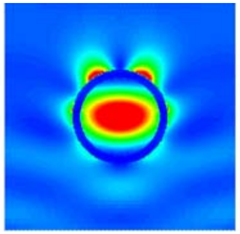
- Sensing (SERS, …)
- medical diagnostics
- medical therapy
- LEDs (directional emission, polarization control)
- nanocavities
- Photovoltaics



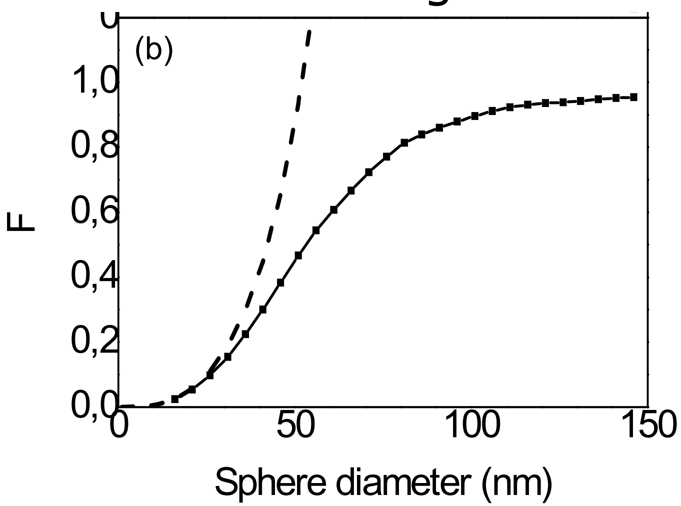




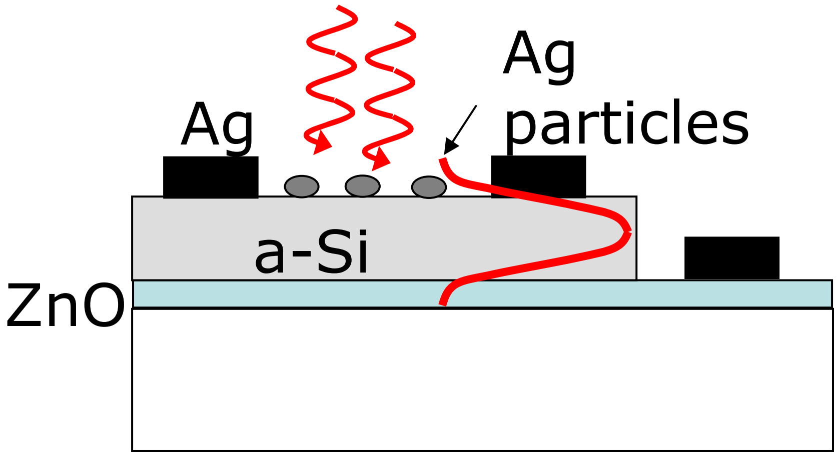




Absorption ~ r^3
Scattering ~ r^6

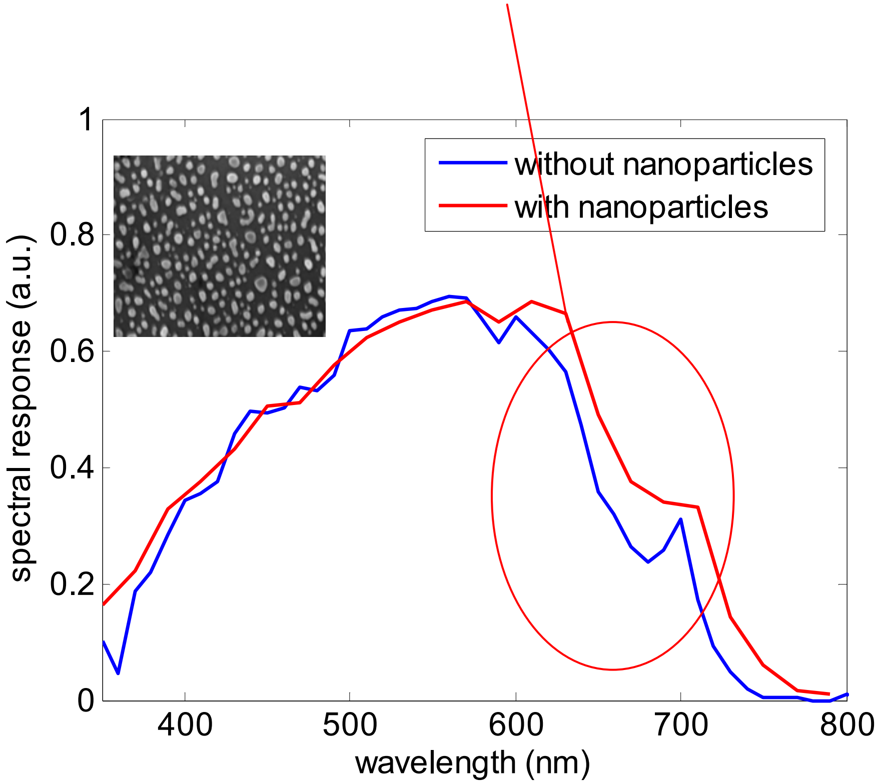


Plasmonic solar cells: light scattering from metal nanoparticles

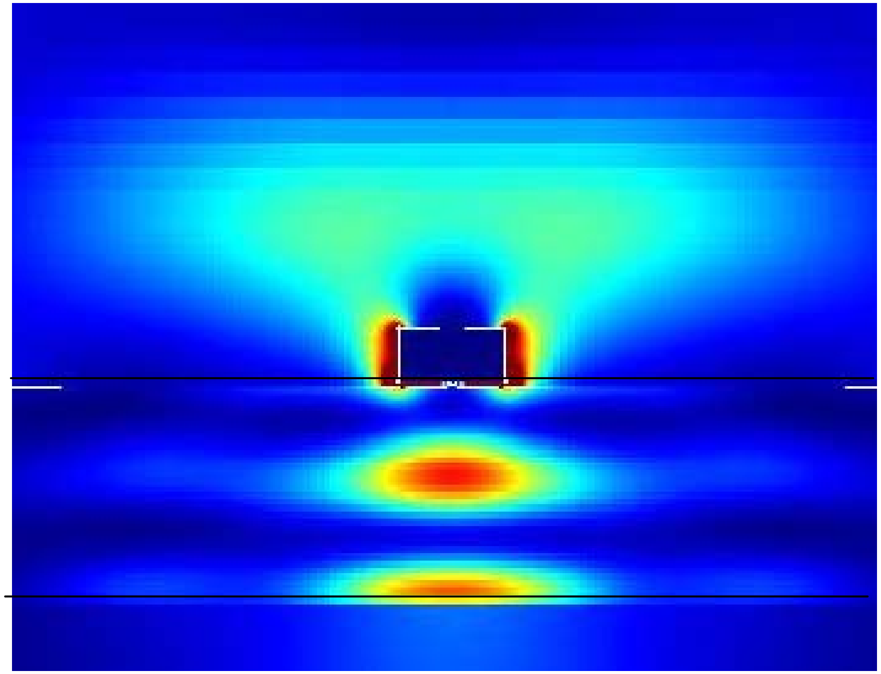


Enhanced light coupling into thin-film solar cells

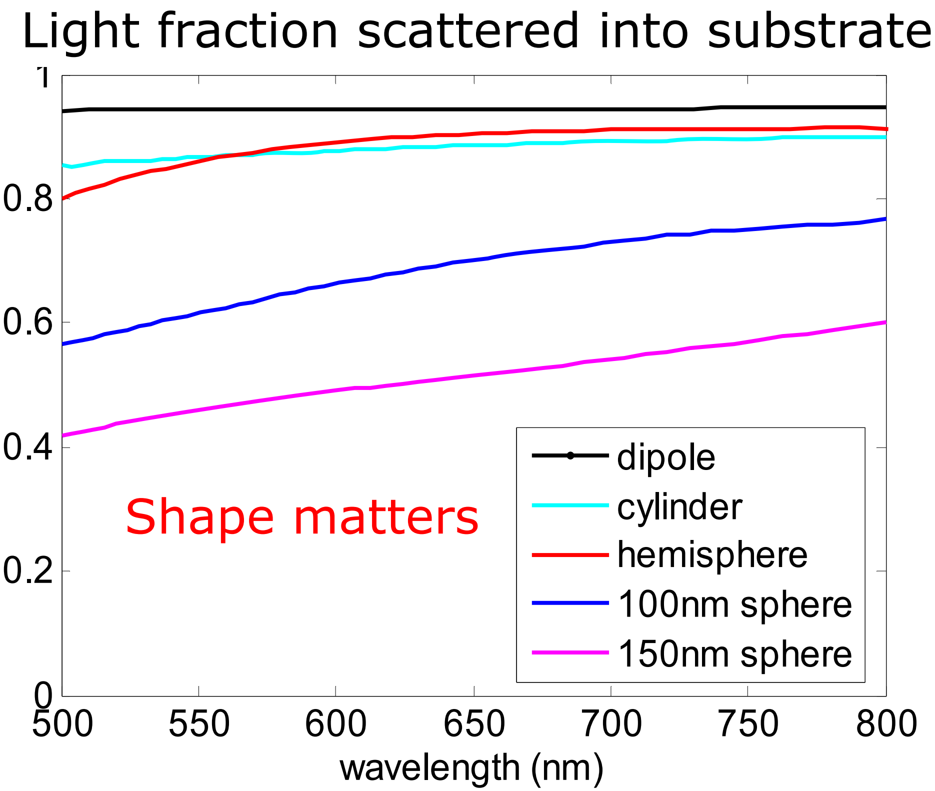
Enhanced red-response



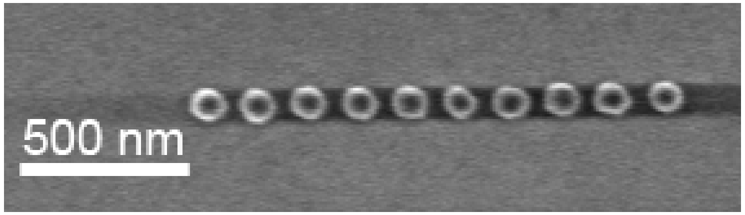
Fraction of light scattered into thin-film solar cell substrate

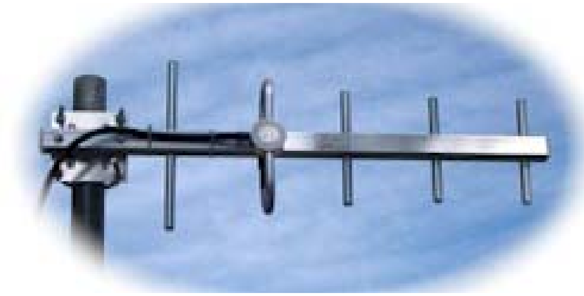


FDTD results



Metal particle arrays as nanoscale antennas





10 MHz – 10 GHz range
1 active, several passive dipole

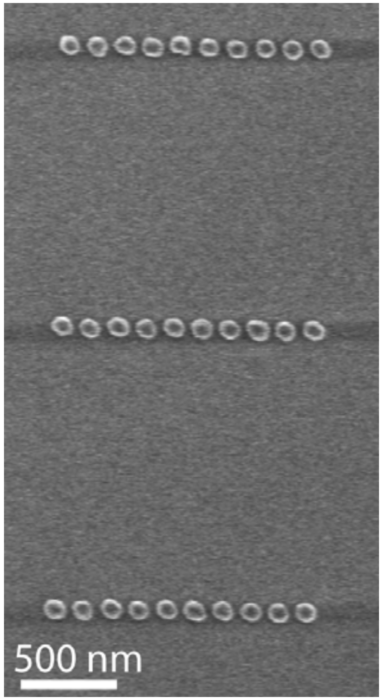
Dipole chains as antennas:

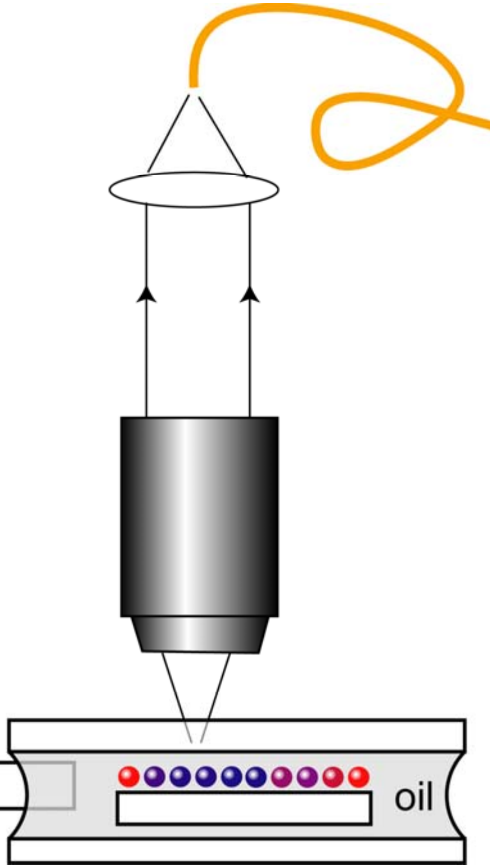
- Many dipoles couple
- Interference effects
- Retardation effects

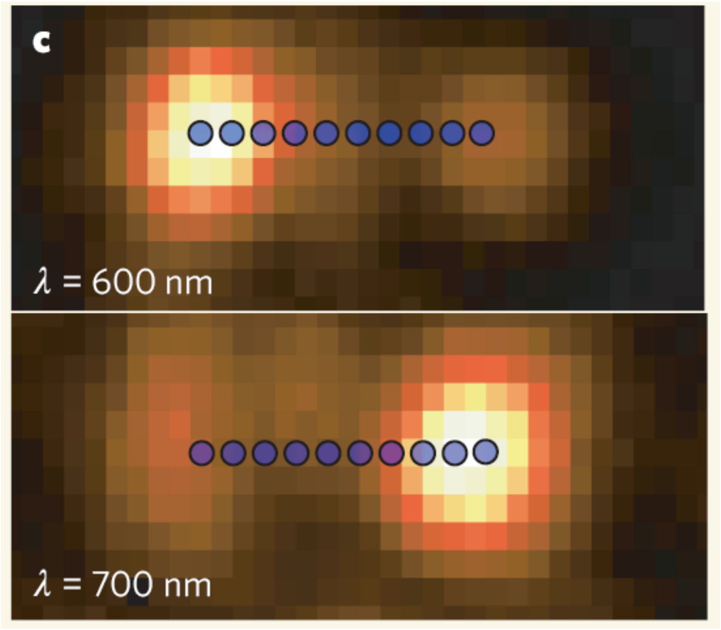
Nano Lett. **7**, 2004 (2007)

René de Waele, Femius Koenderink

Metal nanoparticle antenna: confocal imaging



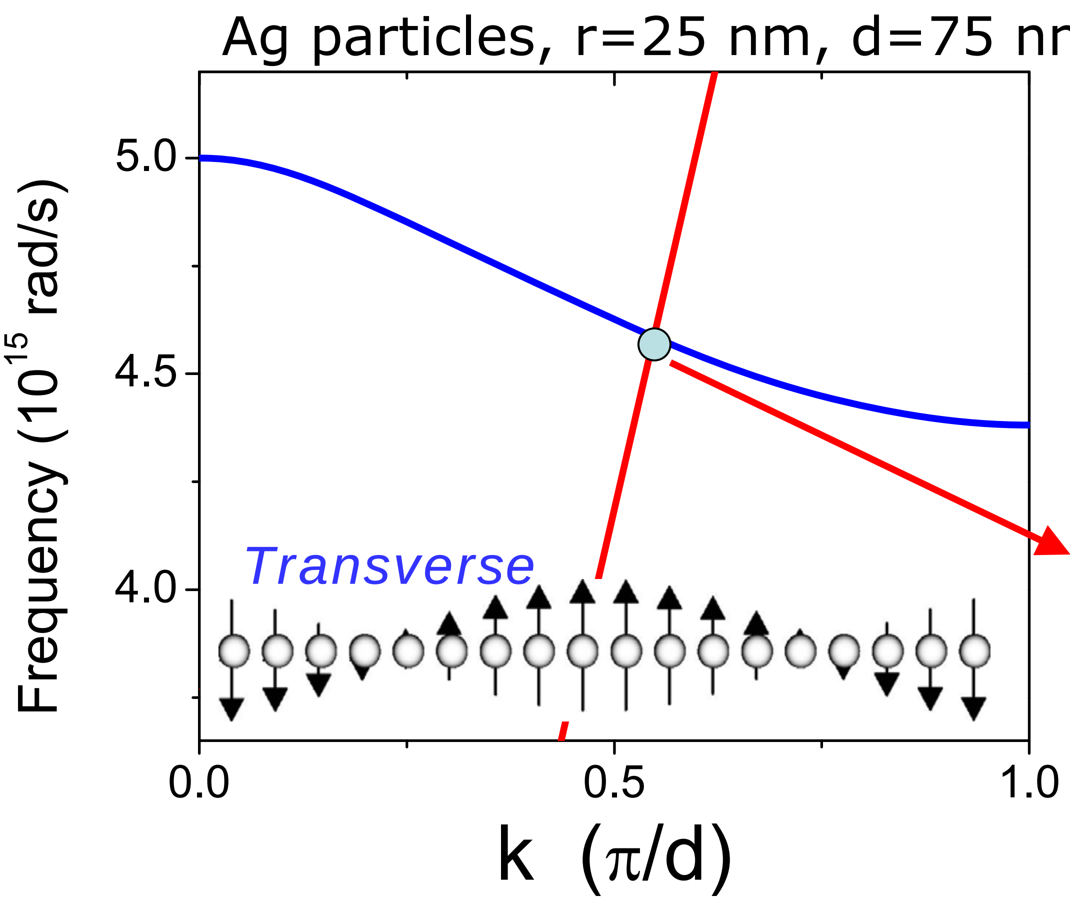




Nano Lett. **7**, 2004 (2007)

René de Waele, Femius Koenderink

Dispersion: Quasistatic approximation



If Spacing d << l

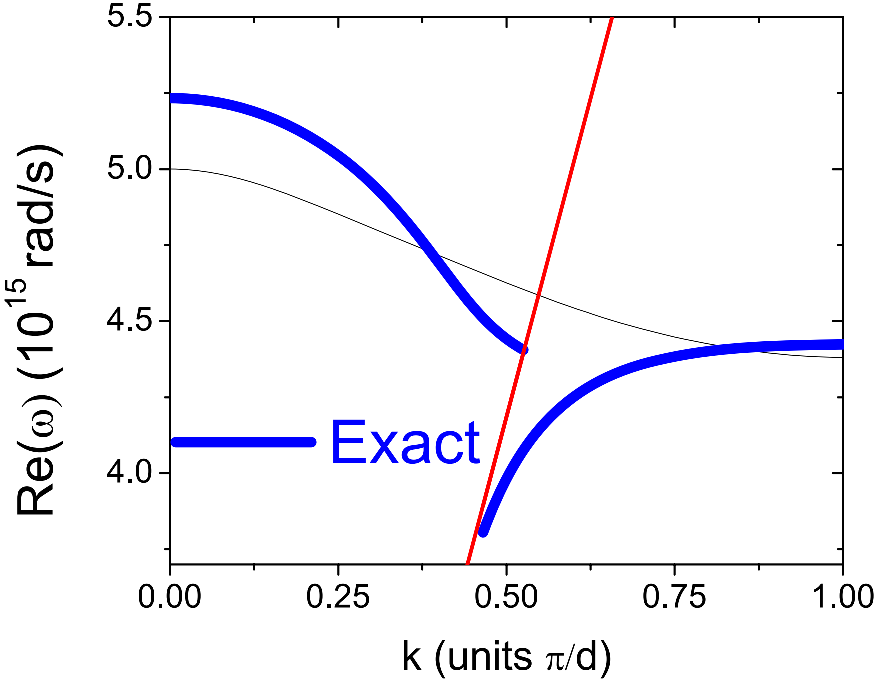
Electrostatics $\mathbf{E} \propto \frac{\mathbf{p}}{d^3}$

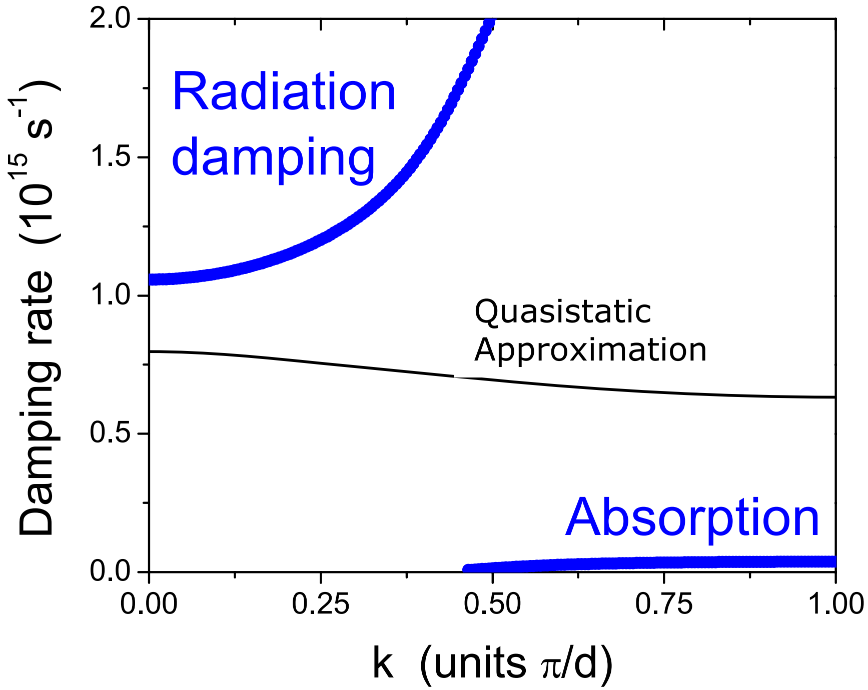
Light line
Coupling to radiation

Quinten et al., Opt Lett (1998), Brongersma et al., PRB (2000)
Weber & Ford, PRB (2004), Citrin, Opt. Lett. (2006)

René de Waele, Femius Koenderink

Metal nanoparticle waveguide: dispersion relation





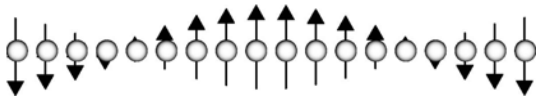
Include retardation, radiation & Ohmic damping

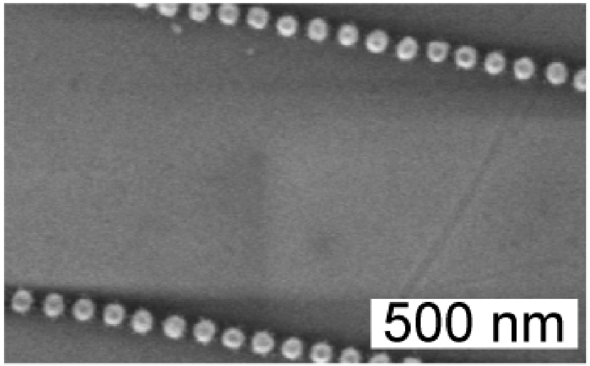
- Splitting into polariton-like bands
- Lower branch: loss time > 100 optical periods
- Propagation length > 10 µm

Phys. Rev. **B 74,** 033402 (2006)

René de Waele, Femius Koenderink

Measure dispersion relation of nanochains

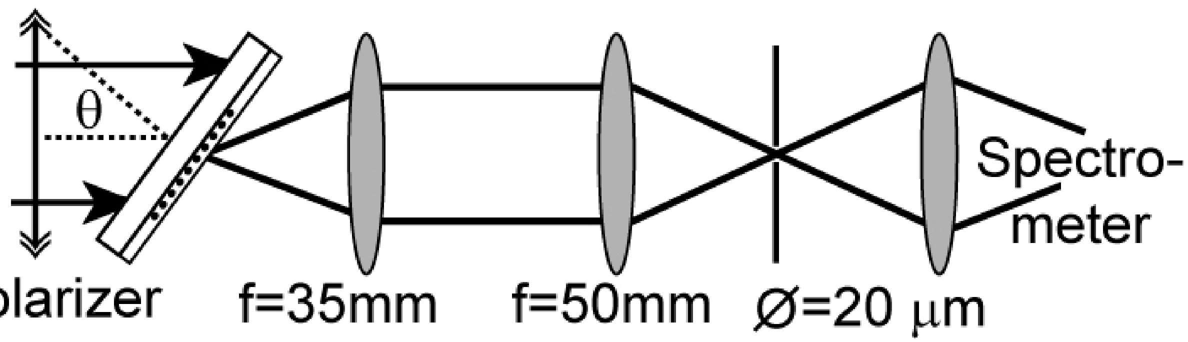




Ag on glass, embedded in PMMA

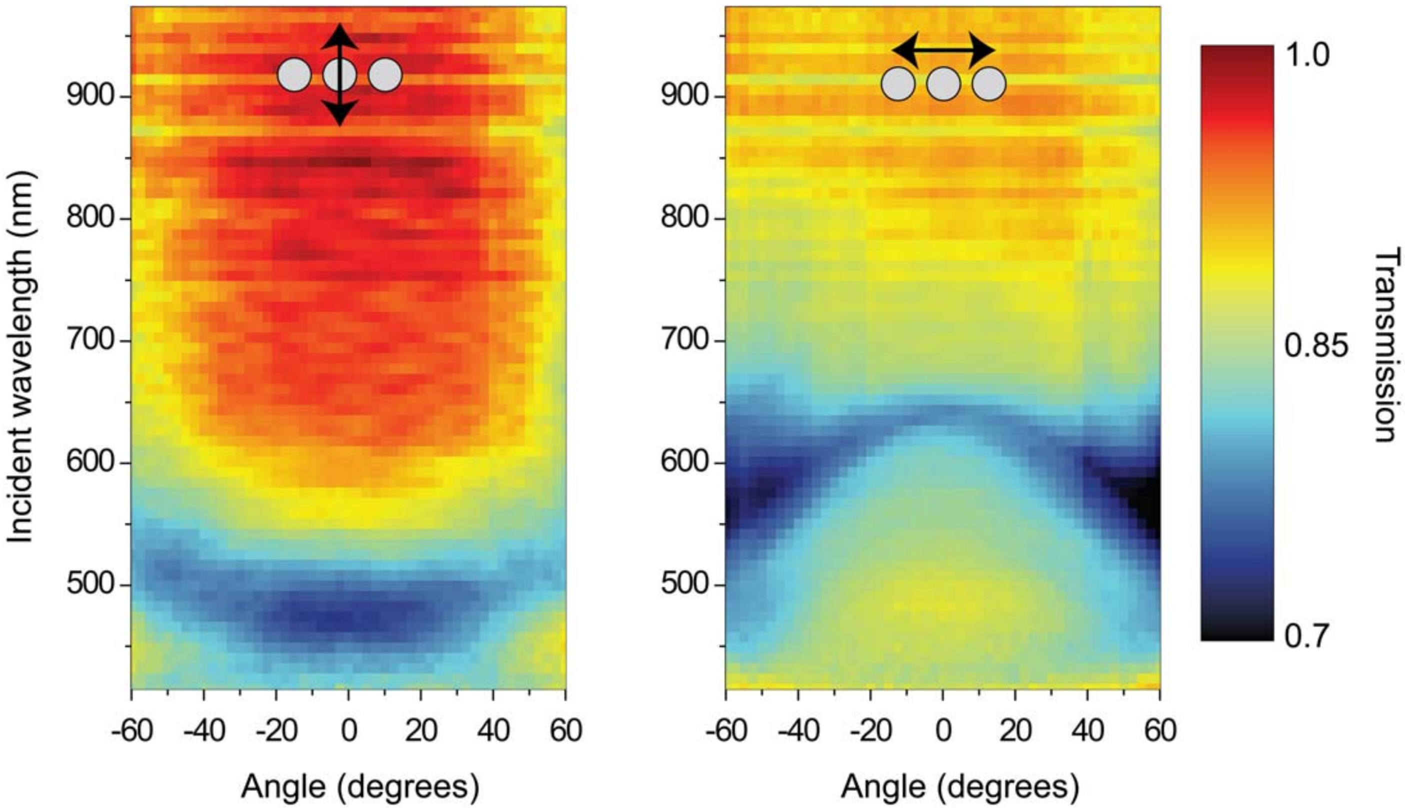
R = 25 nm

D = 150 nm



Extinction spectra

Ag, r=50, d=150 nm



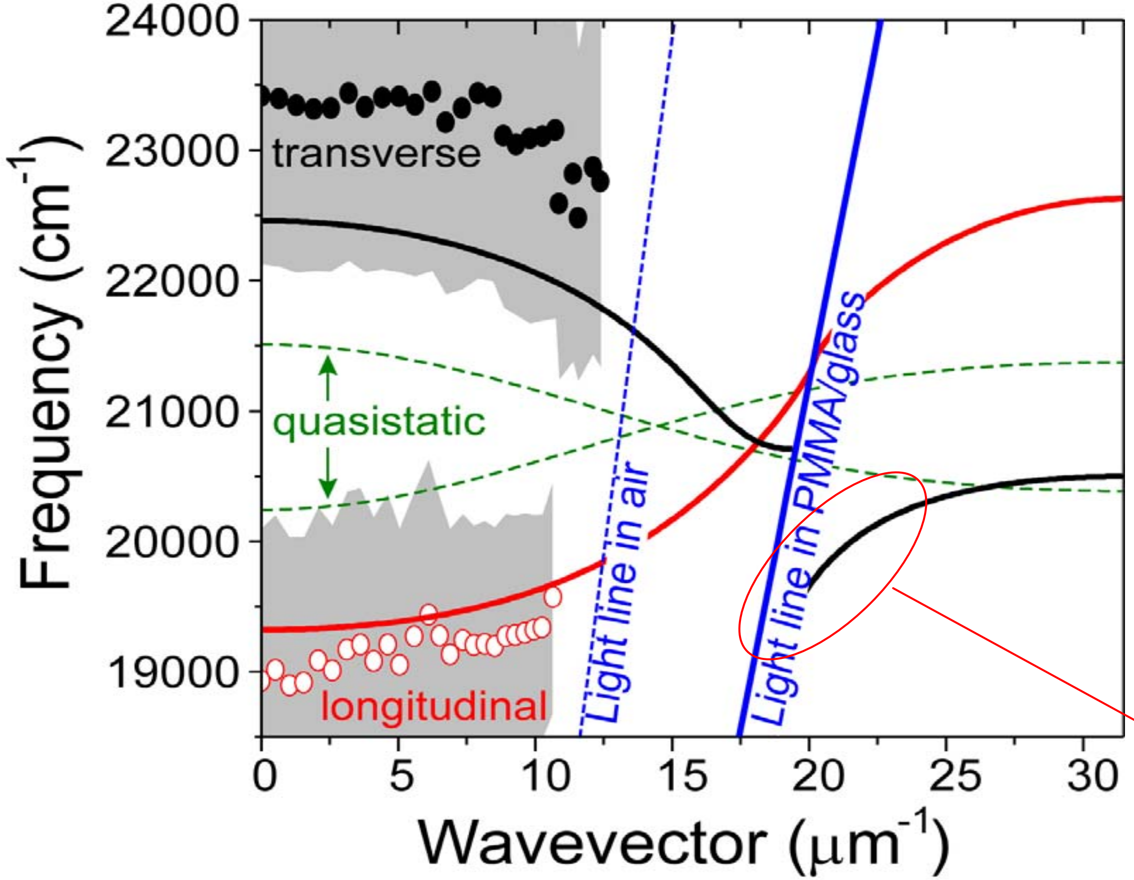
Extinction minimum → plasmon coupling

Phys. Rev. B. **76**, 201403 (2007)

Femius Koenderink, René de Waele

Compare to dispersion relation

Ag, r=30, d=100 nm



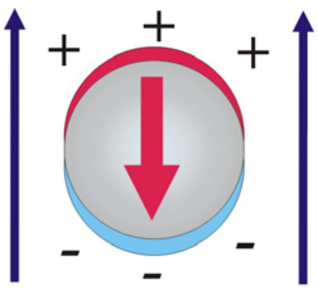
Dynamic calculation: incl. retardation, scattering, Ohmic losses

Dynamic effects are Important

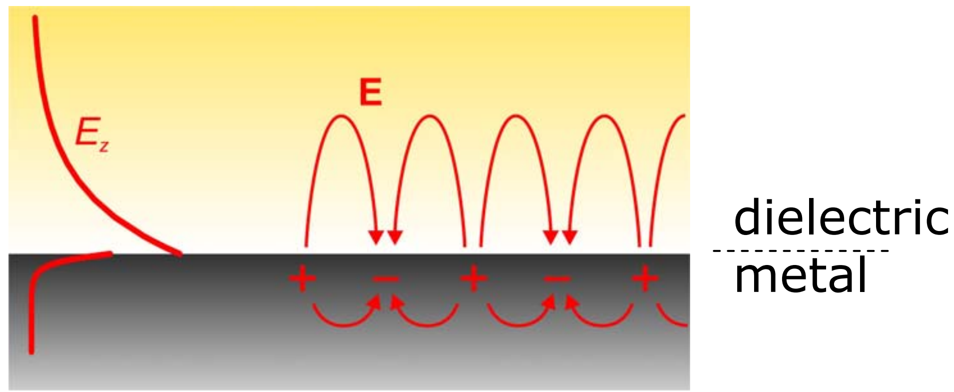
Implications for circuit theory at length scales as small as $\lambda/5$

Propagation length: 5-10 µm

Surface plasmons: electromagnetic resonances in the visible

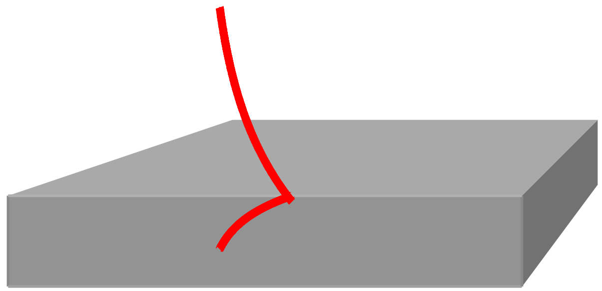


Localized plasmon oscillation

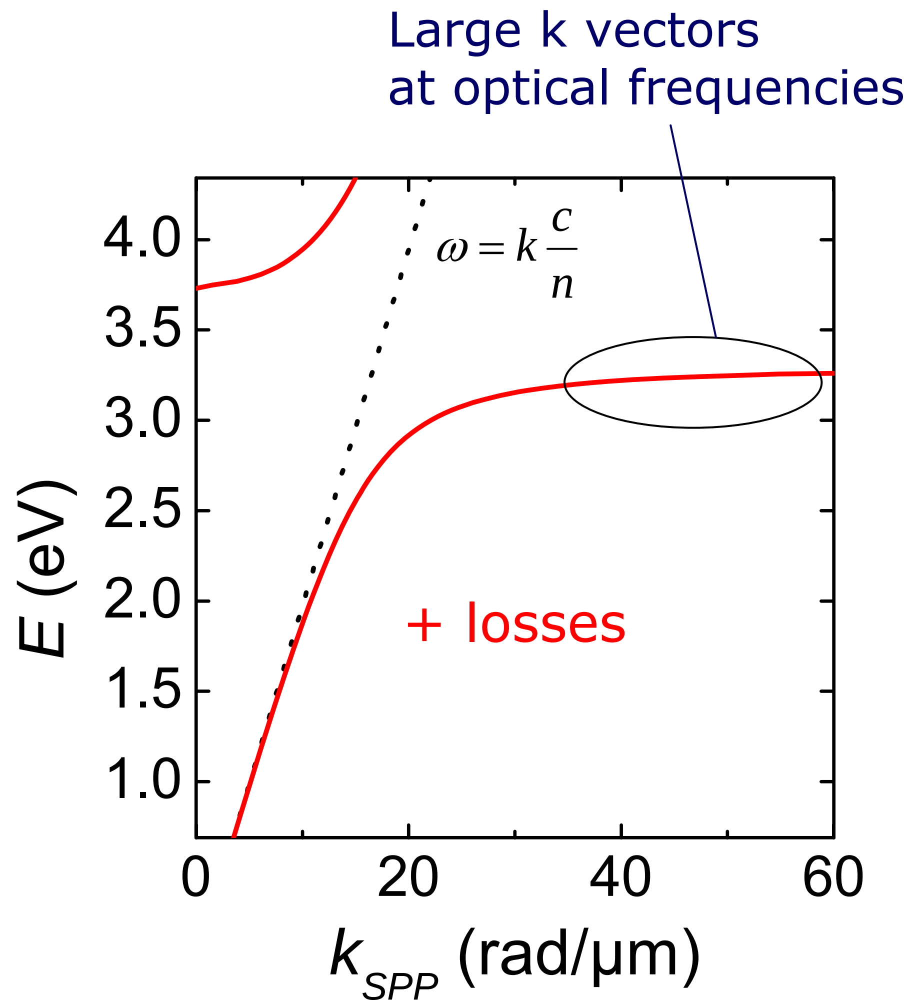


Propagating surface plasmon polariton (SPP)

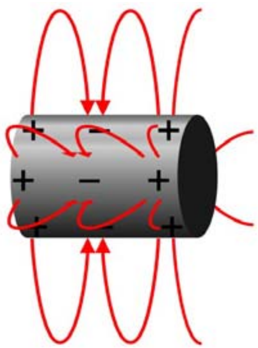
Dispersion of surface plasmon polaritons

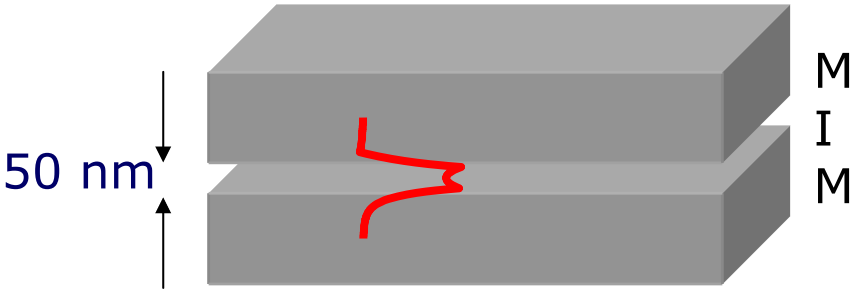


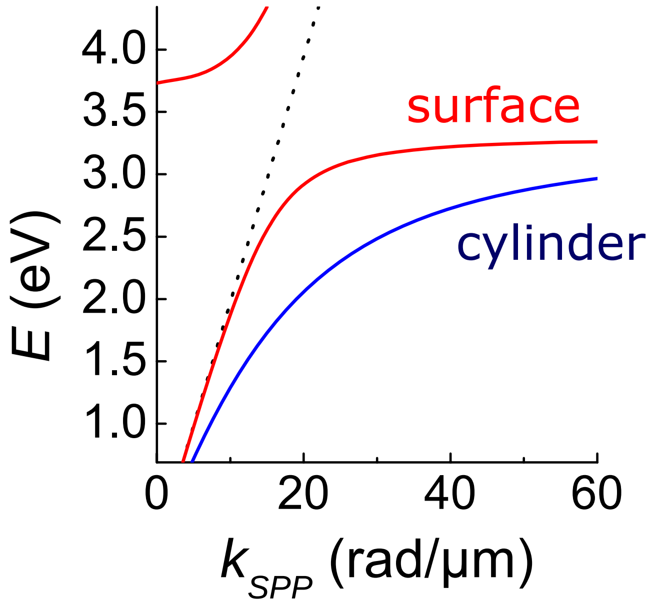
$$k_x = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2}$$

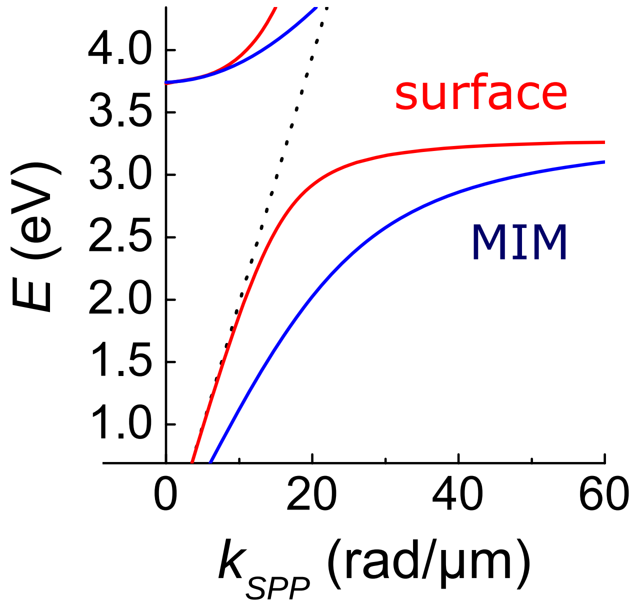


SPP dispersion designed by geometry



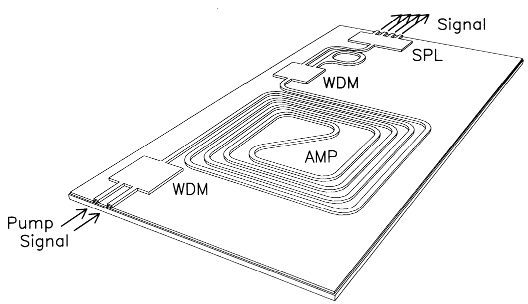


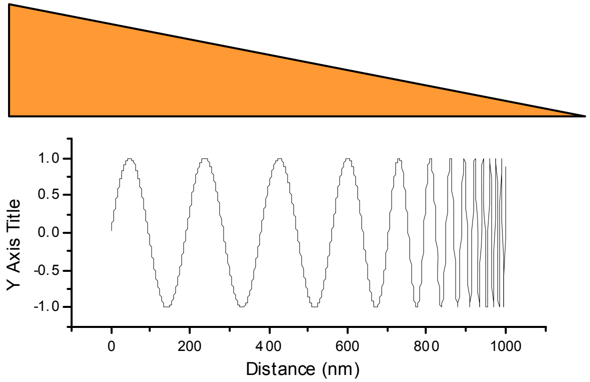




Two-dimensional optics with SPPs

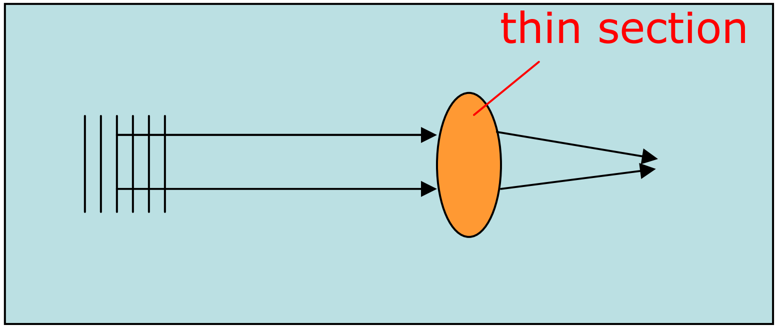
Nanoscale plasmonic integrated circuits



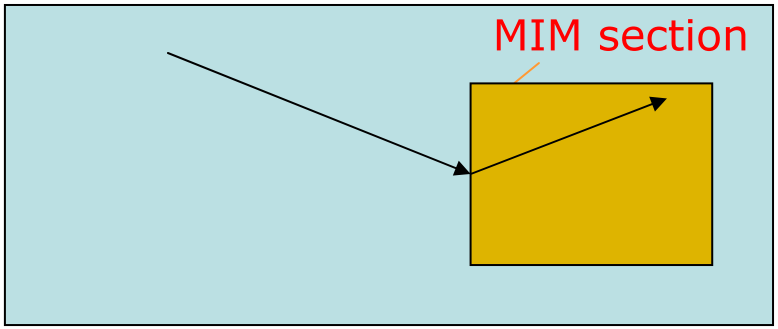


Plasmonic concentrator

Plasmonic lens



Negative refraction



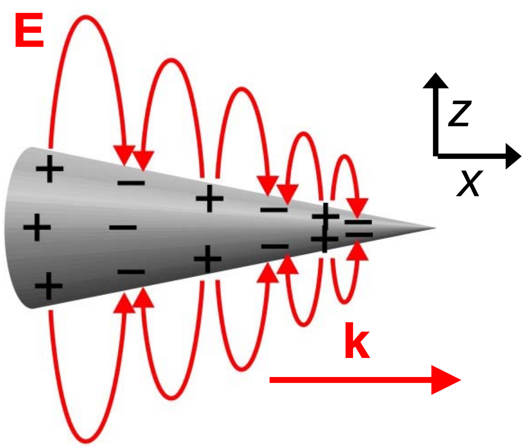
And much more .....

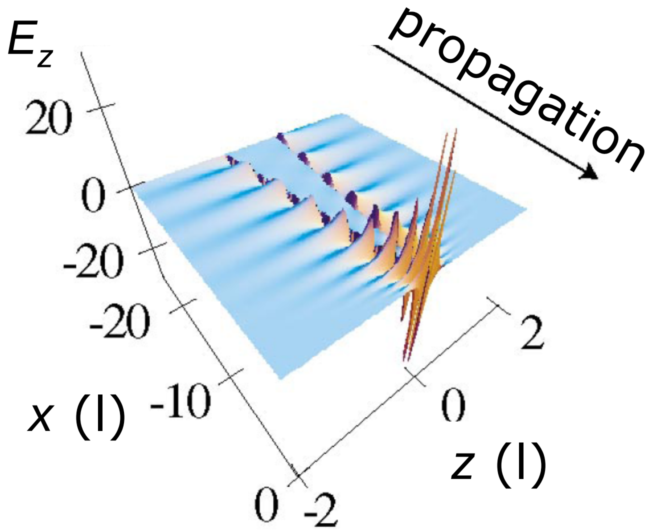
Plasmonic toolbox:

ω, $\varepsilon(\omega)$, d engineer $\lambda(\omega)$

Surface plasmon nanofocusing

- Focusing in tapered metal cylinder



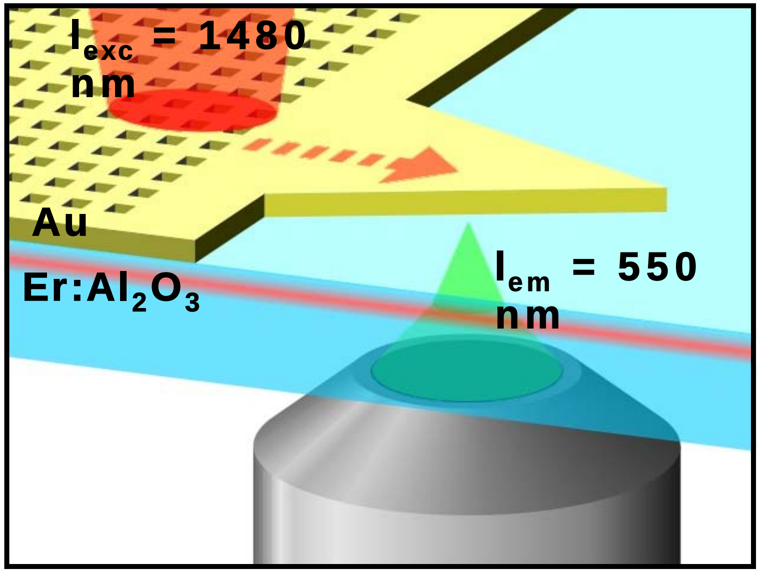


Stockman, PRL ***93****, 137404 (2004)*

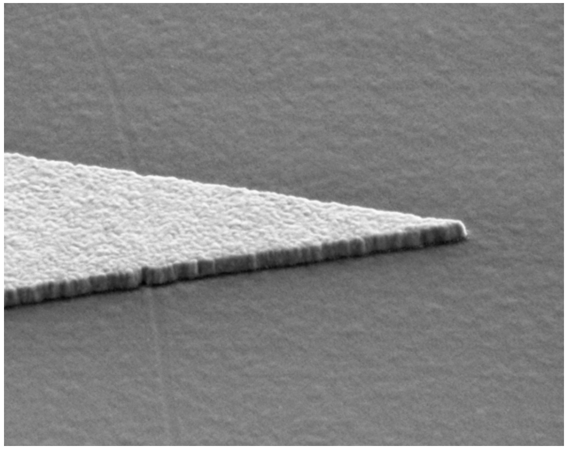
- Strong confinement and field enhancement near taper tip
- Focusing of fundamental cylindrical SPP mode

Nanofocusing in tapered waveguides

- Infrared SPPs (λ_{exc}=1480 nm) excited along Au/Al_2O_3 interface
- Erbium ions in substrate as probe for plasmon propagation

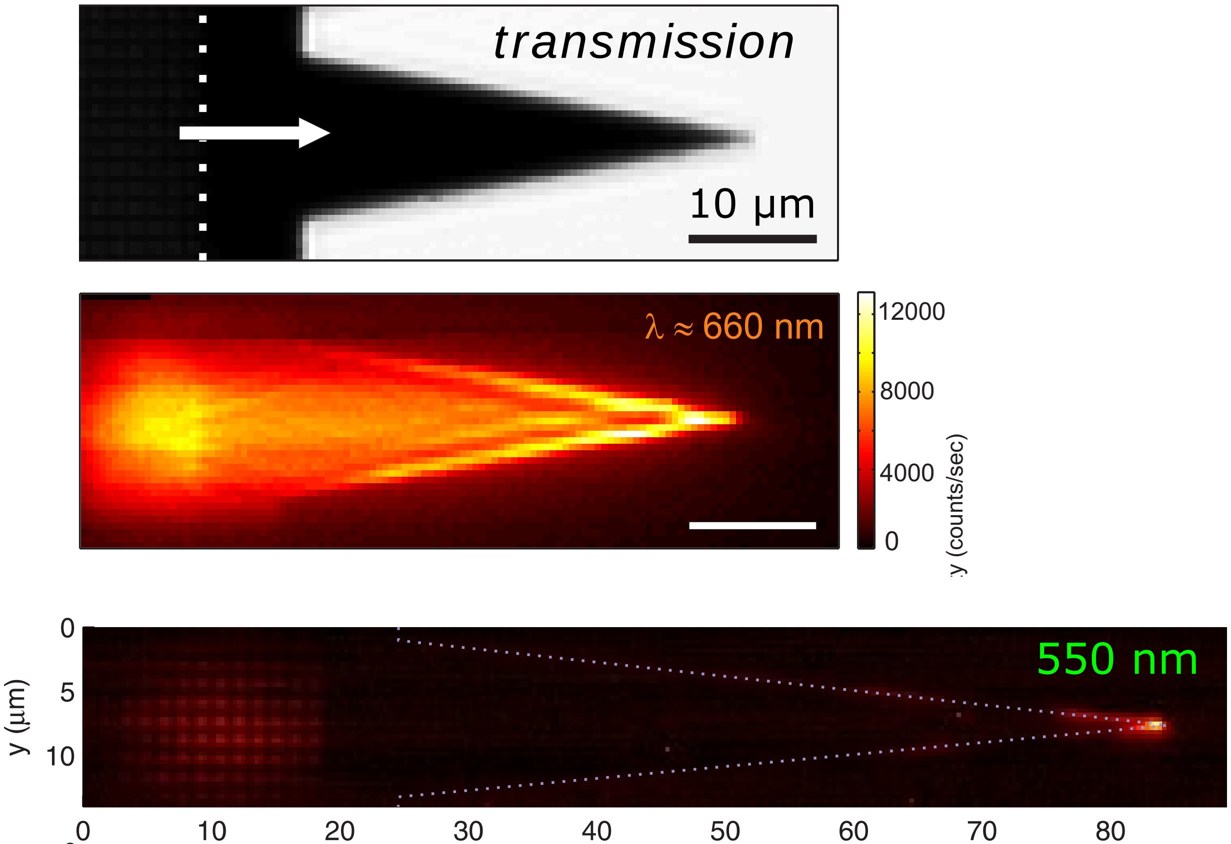


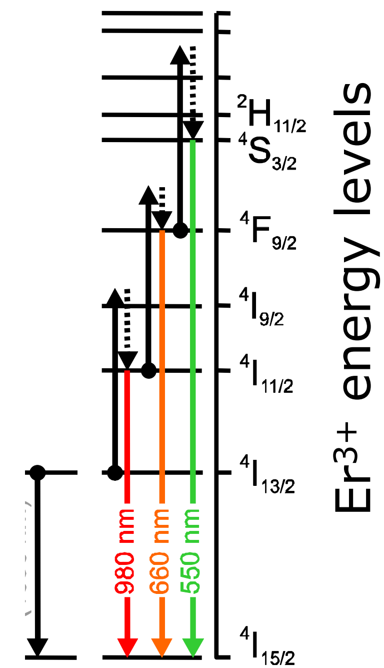
Au film thickness: 100 nm
apex diameter: ~60 nm



ref. Weeber et al., PRB 64, 045411 (2001)

SPP concentration in tapered waveguides





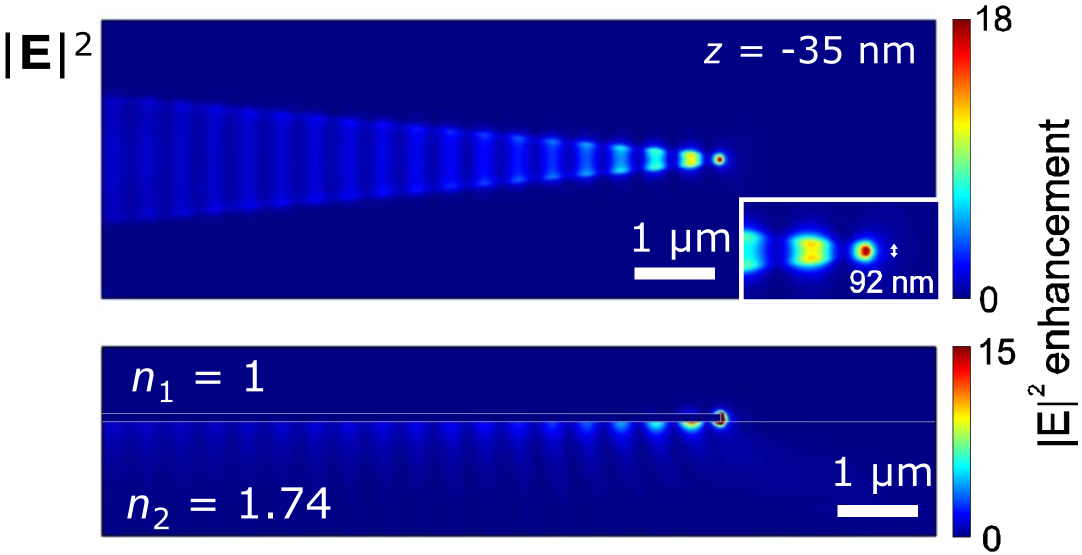
λ_{exc} = 1480 nm

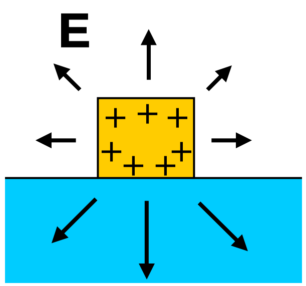
Guiding and concentration observed to $\lambda/8$

Nano Lett. **7**, 334 (2007)

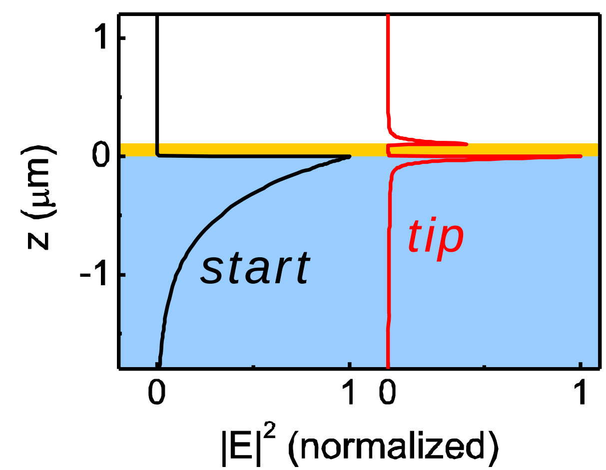
Ewold Verhagen, Kobus Kuipers

FDTD Simulations: nanofocussing to < 100 nm





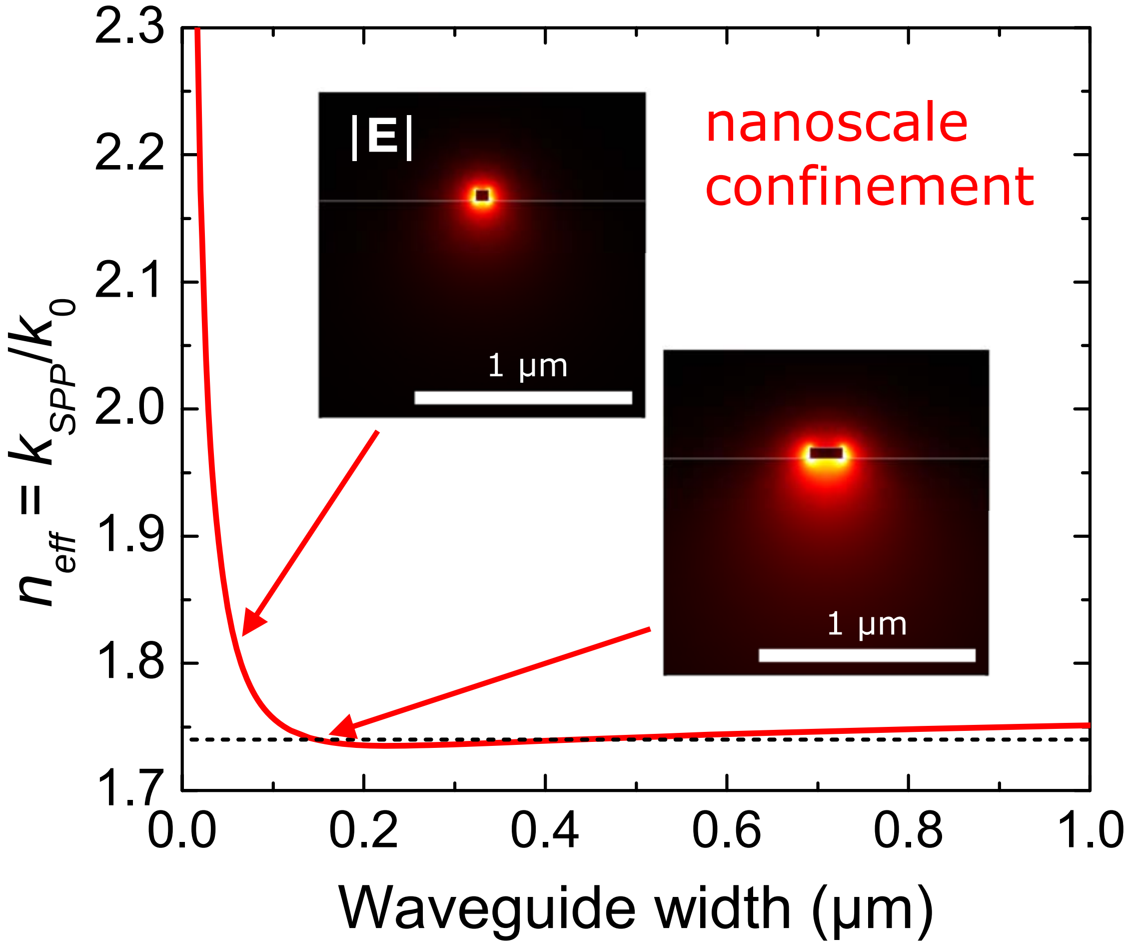
- Nanofocusing predicted: 100 x $|\mathbf{E}|^2$ at 10 nm from tip
- 3D subwavelength confinement: 1.5 µm light focused to 92 nm (λ/16)
- limited by taper apex (60 nm)

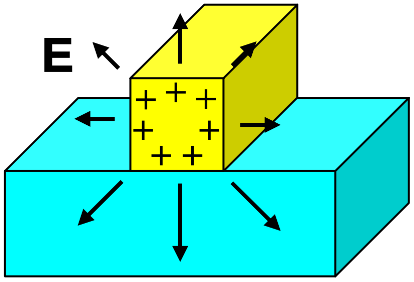


Optics Express **16**, 45 (2008)

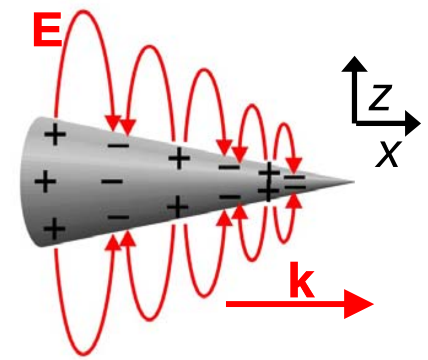
Ewold Verhagen, Kobus Kuipers

SPP modes in stripe waveguides

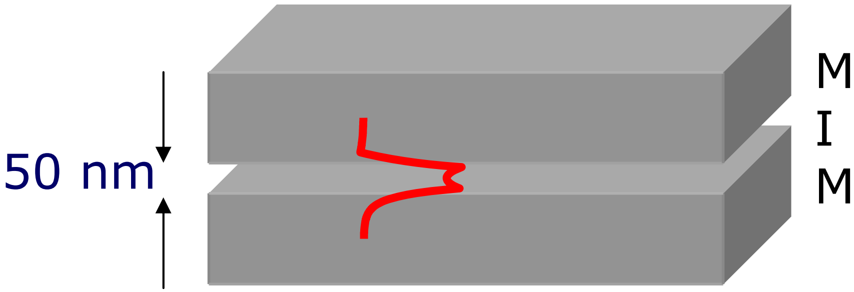




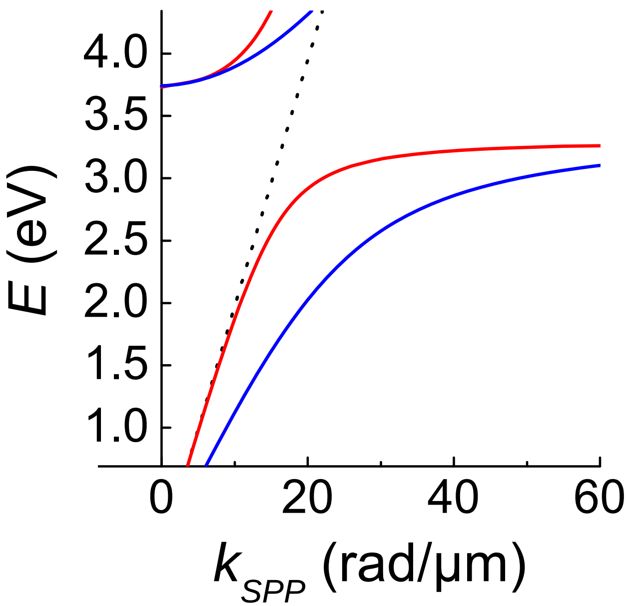
Field symmetry at tip similar to SPP mode in conical waveguide

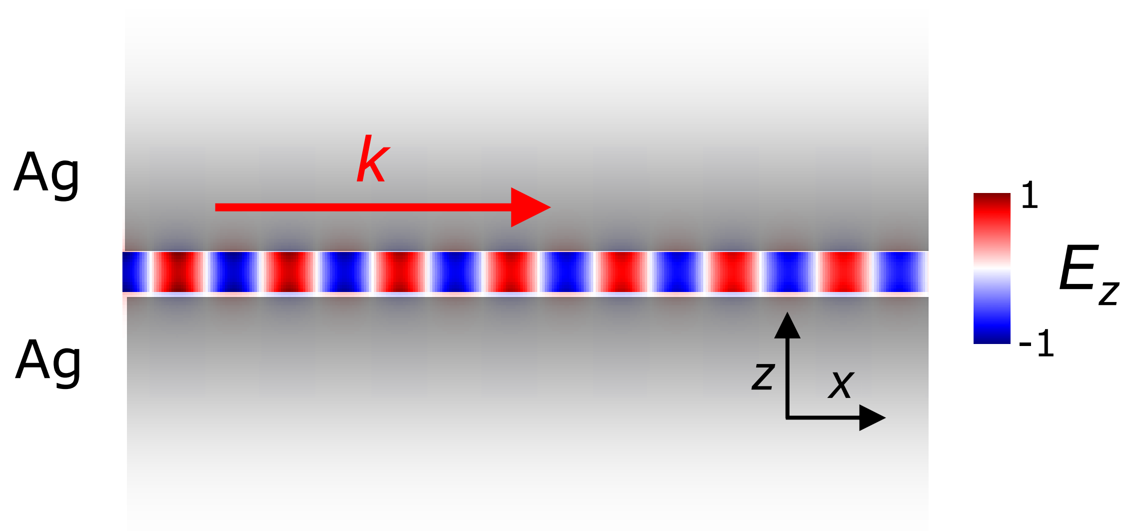


Metal-Insulator-Metal (MIM) waveguides

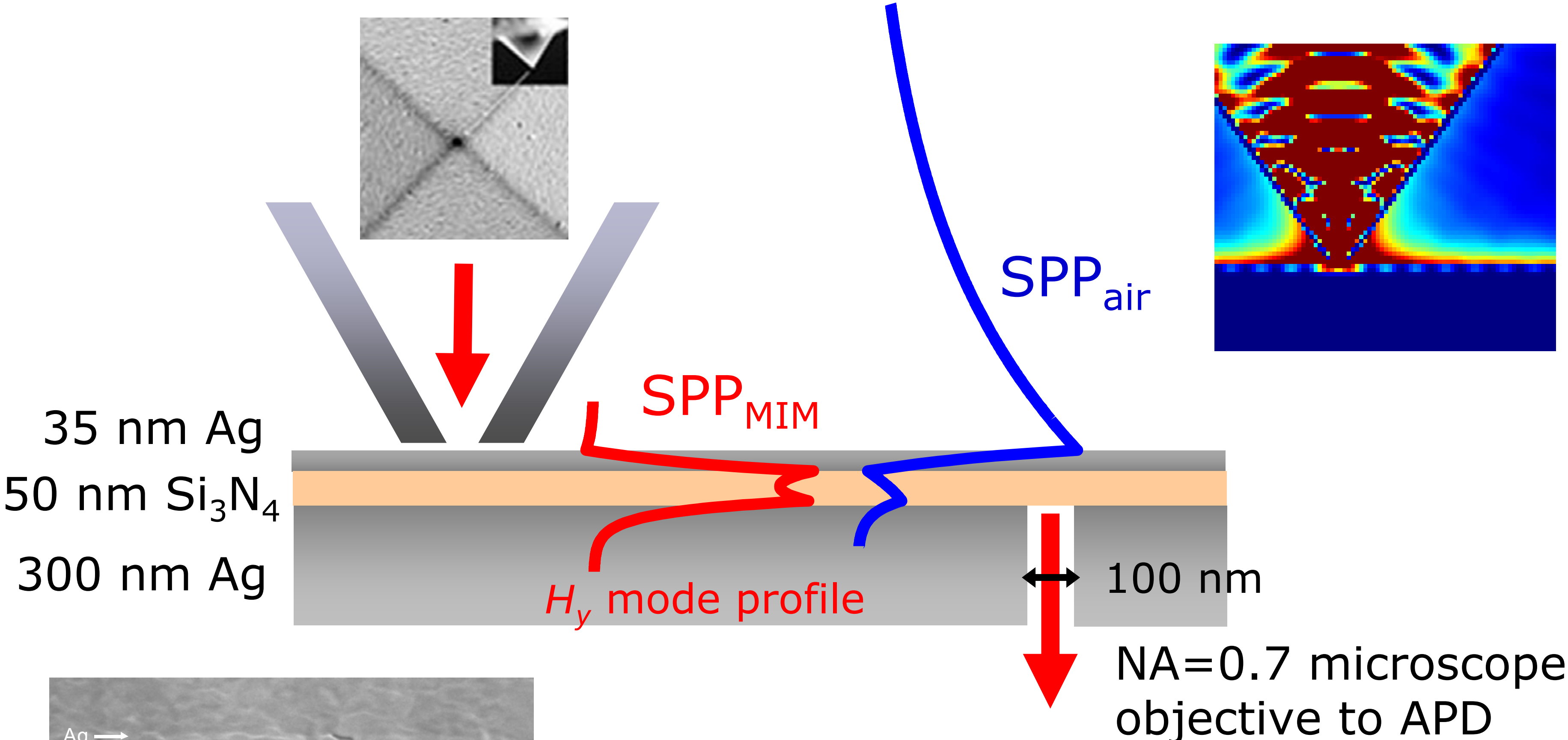


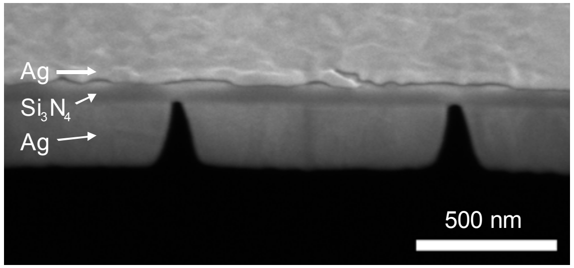
- Strong confinement
- Short wavelength
- Relatively small loss





Near-field probing of MIM modes





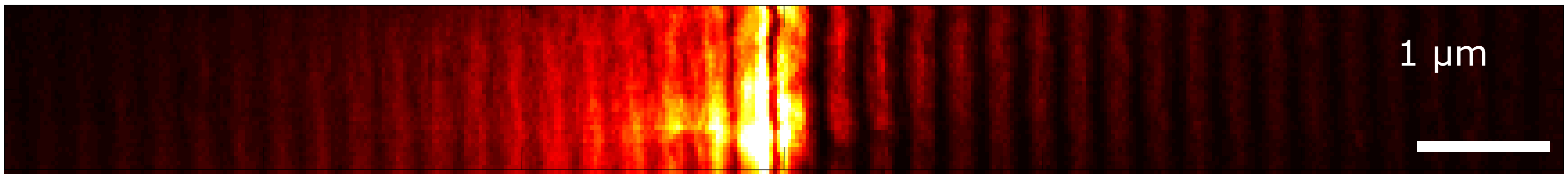
MIM and surface SPP waves interfere

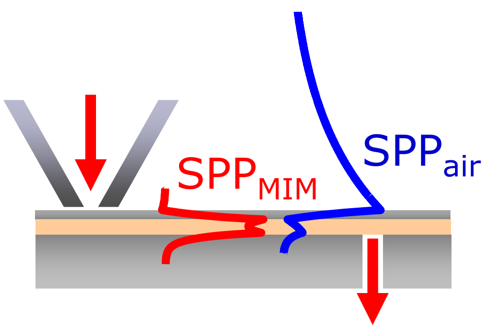
Ewold Verhagen, Jen Dionne

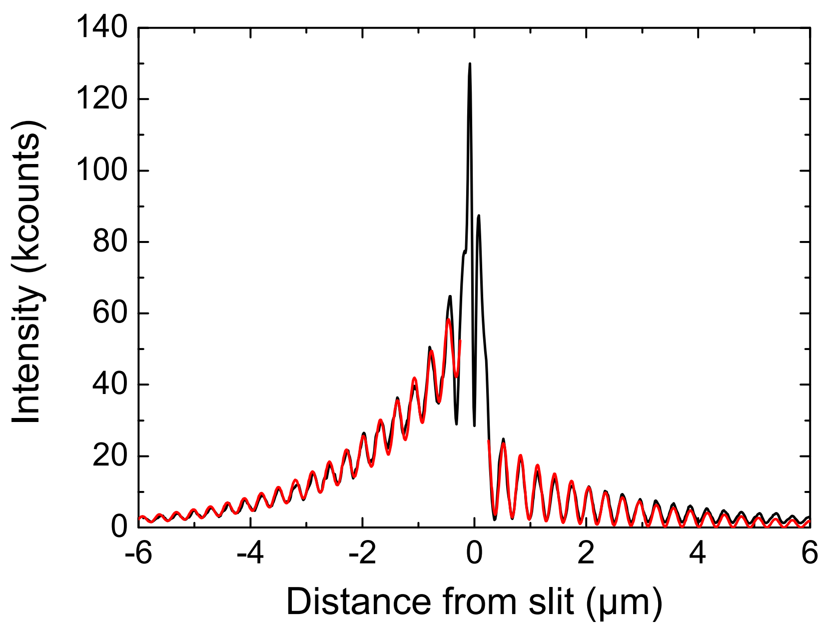
Measuring the SPP_{MIM} wave vector

λ_{exc} = 640 nm

slit position



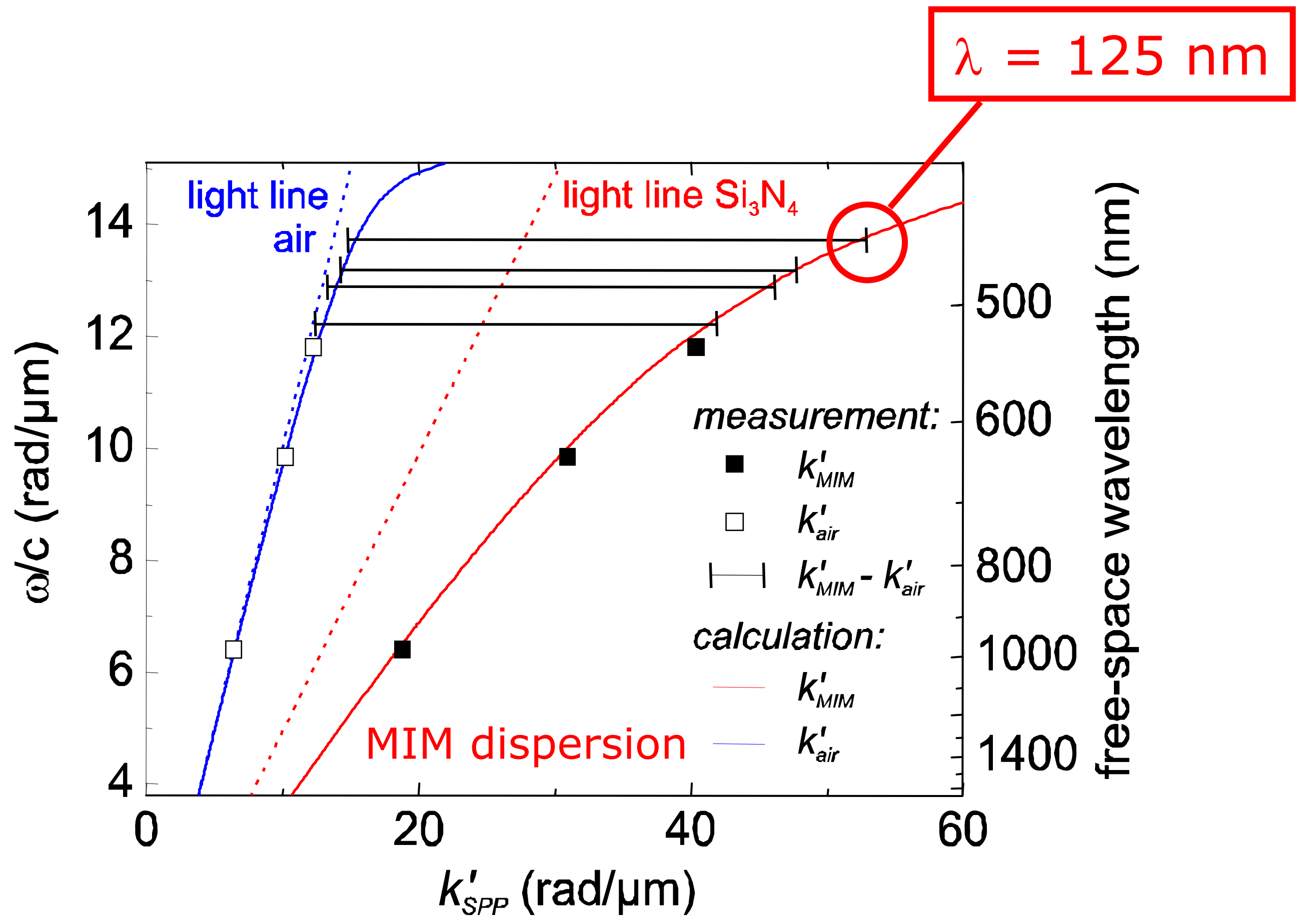




$$\Delta k' \equiv k'_{MIM} - k'_{air}$$

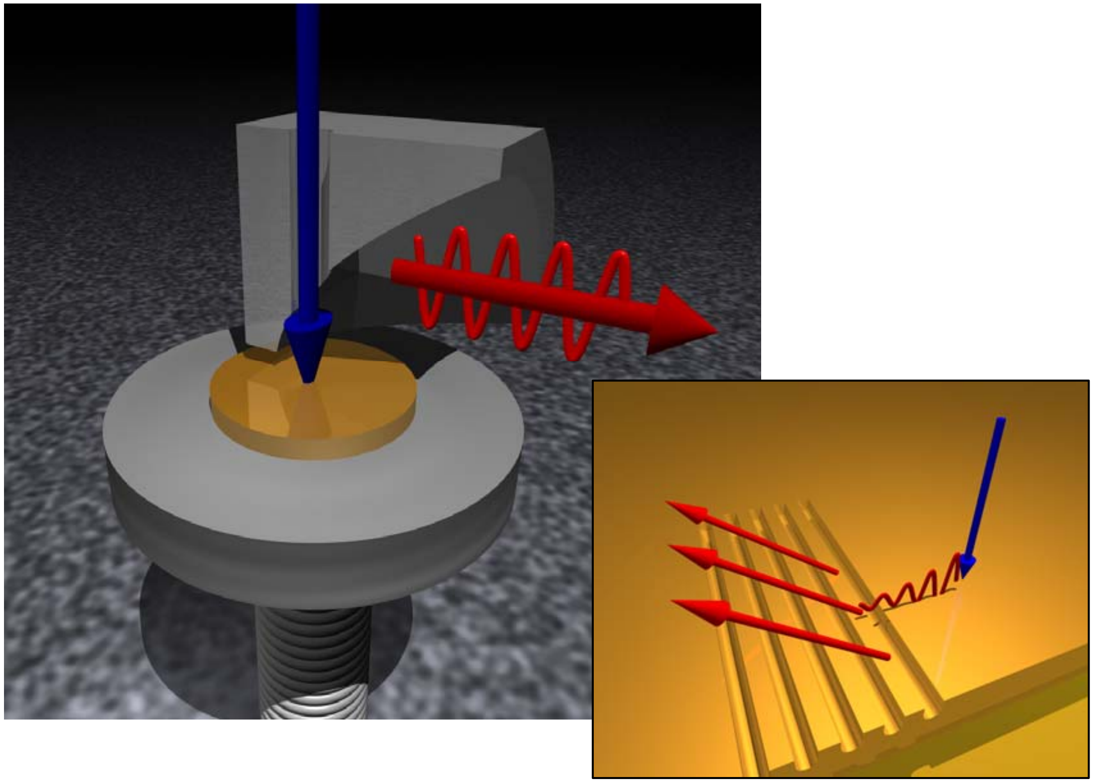
Ewold Verhagen, Jen Dionne

Obtaining the MIM dispersion curve

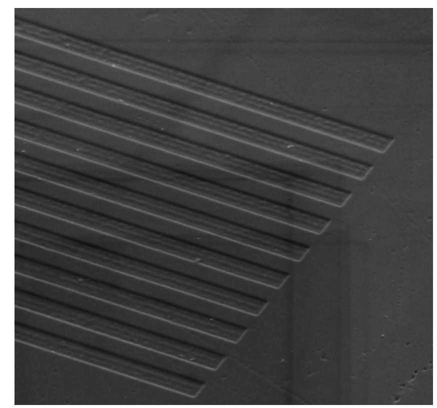


Ewold Verhagen, Jen Dionne

Electron-beam excitation of SPPs: cathodoluminescence (30 keV)



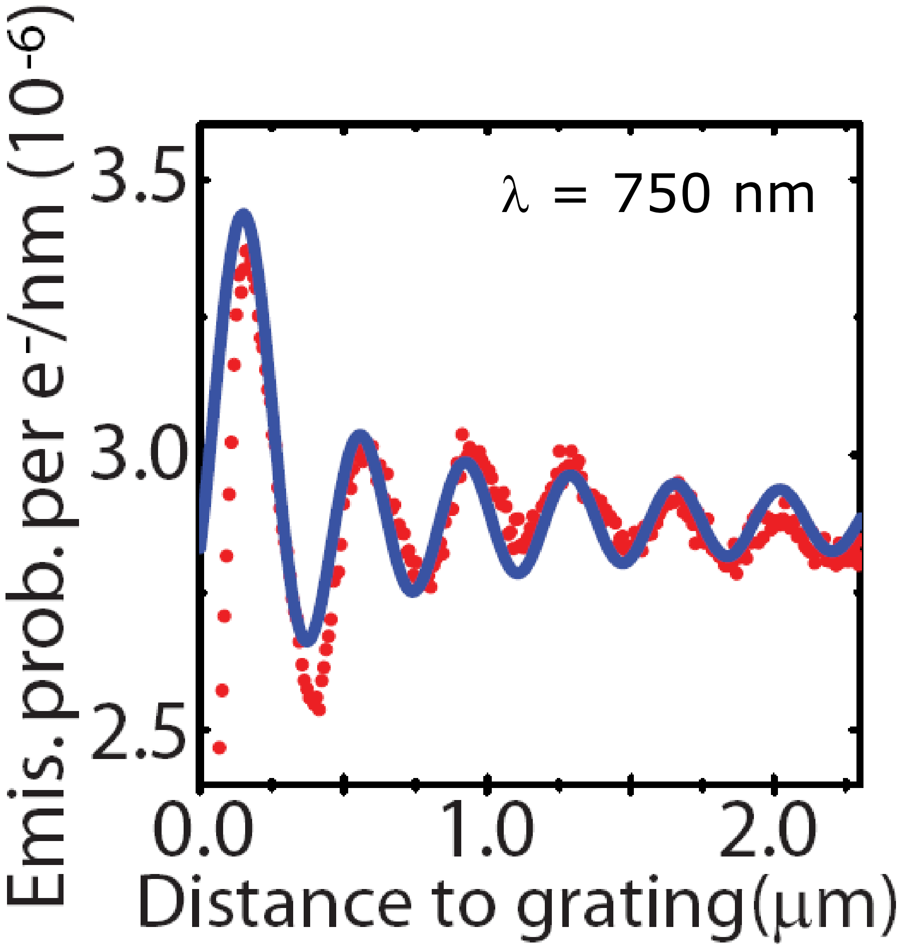
Grating structured with focused ion-beam into single crystalline Au

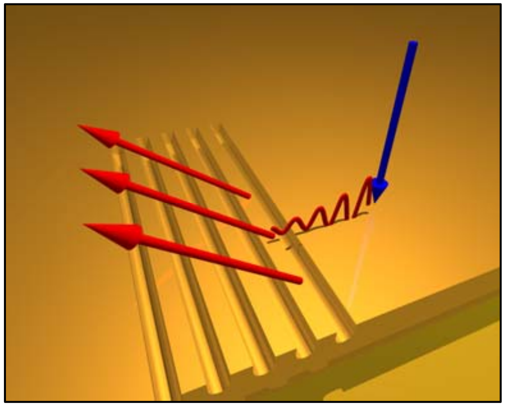


- Broadband excitation of SPPs at nanoscale resolution
- Detection of far-field radiation with parabolic mirror

Marin Kuttge, Ernst Jan Vesseur

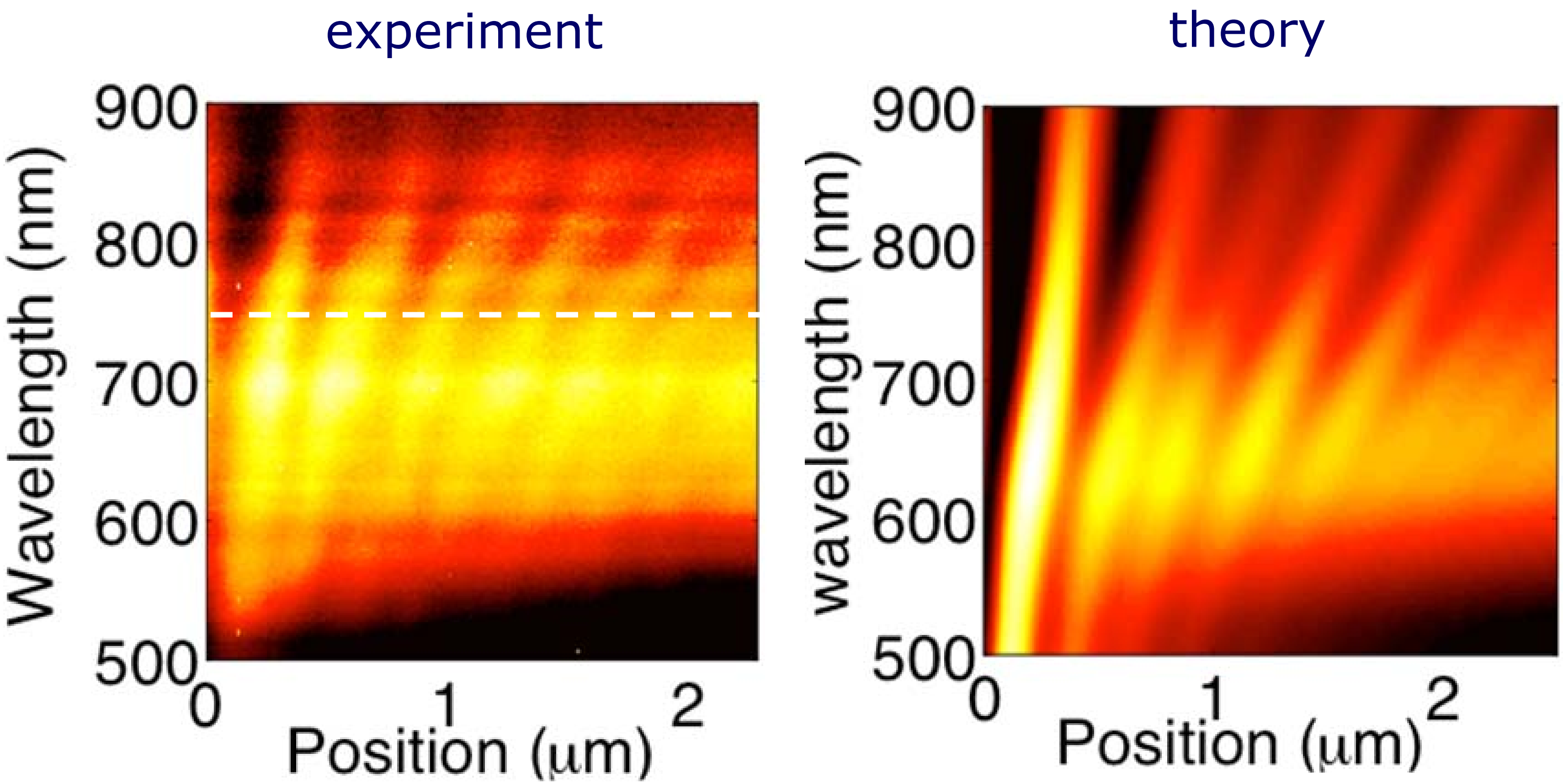
CL emission versus distance from grating





Martin, Kuttge, Ernst Jan Vesseur

Spectroscopic CL scan near grating: Probing the plasmonic density of states

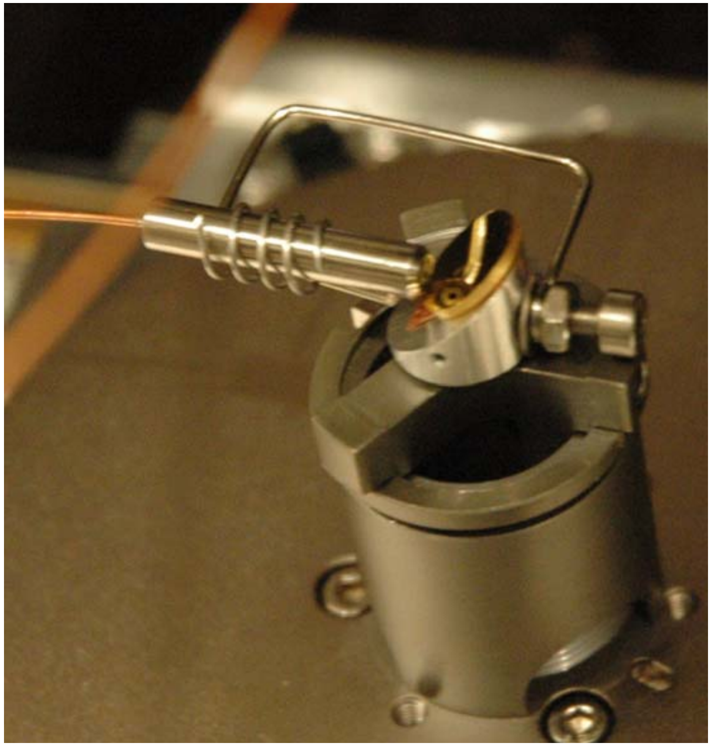


Martin Kuttge, Henri Lezec, Ernst Jan Vesseur

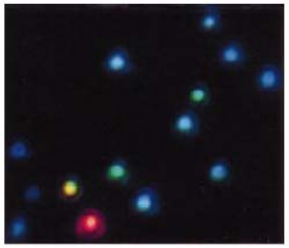
Focussed ion beam milling of plasmonic nanostructures; rapid prototyping

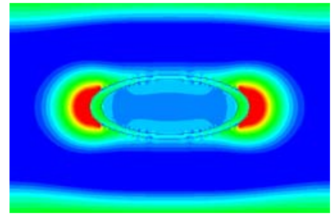
30 keV Ga ion beam

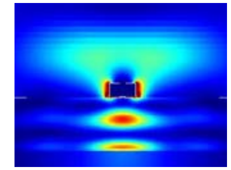
in-situ FIB and CL



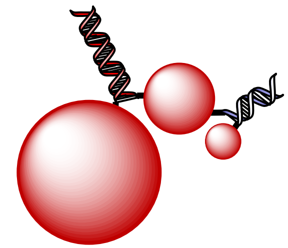
Martin Kuttge, Henri Lezec, Ernst Jan Vesseur

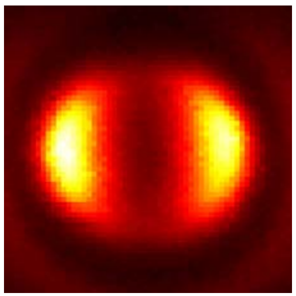


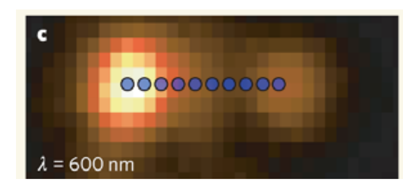


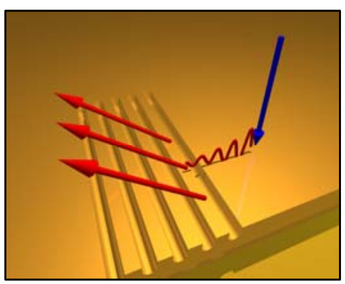


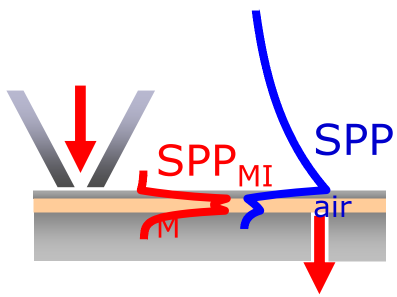
Plasmonics
optics at the nanoscale

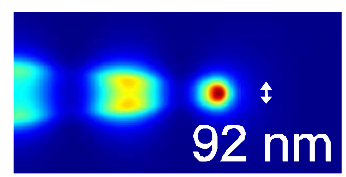












For details/references visit: www.erbium.nl