Imaging Surface Plasmons

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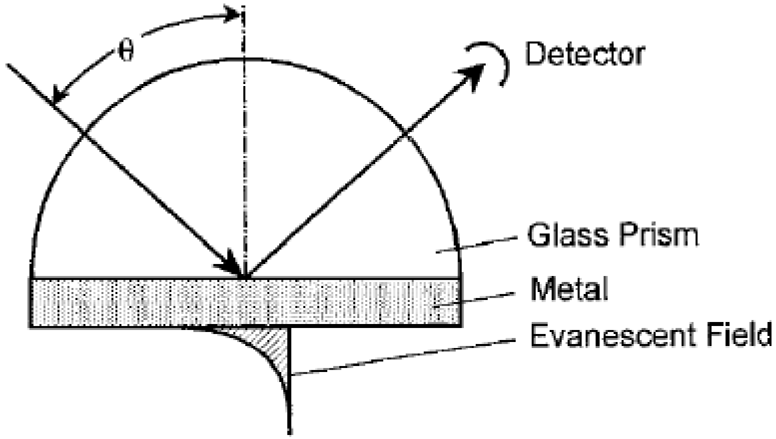
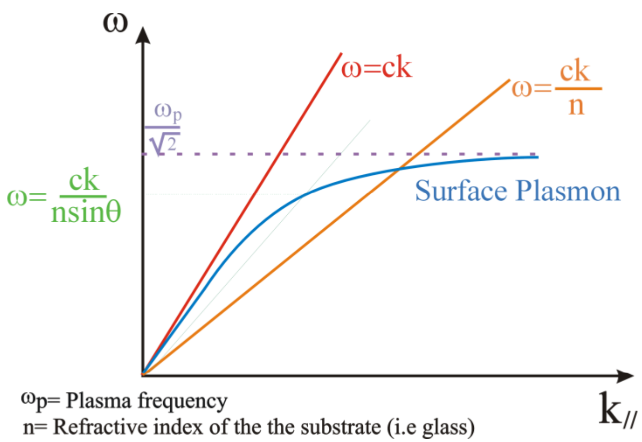
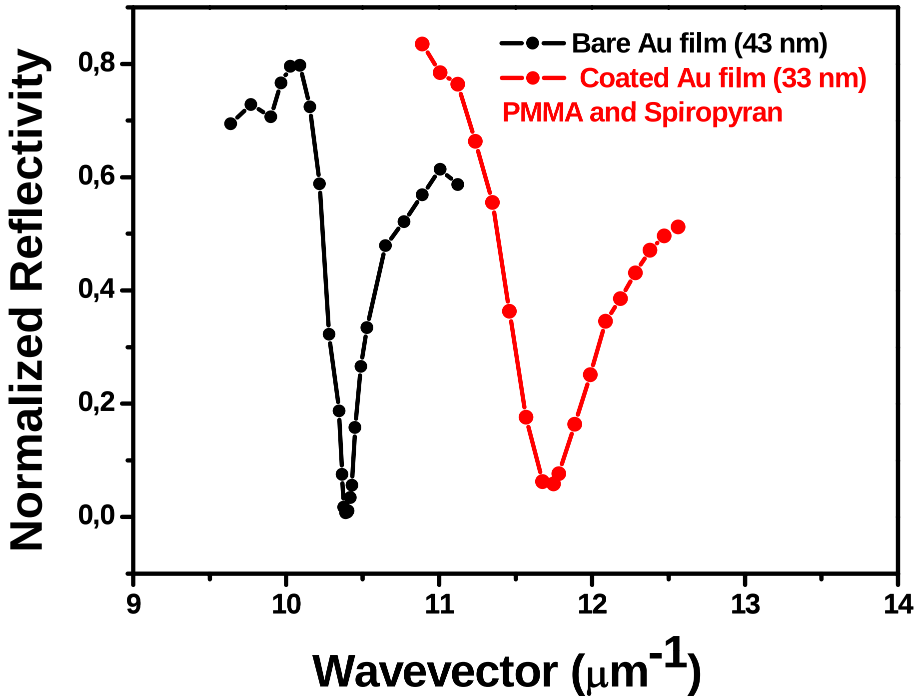
France

(almost) All there is to know about plasmons in 3 curves

1 **Reflectivity curve (Attenuated Total internal Reflection geometry)**







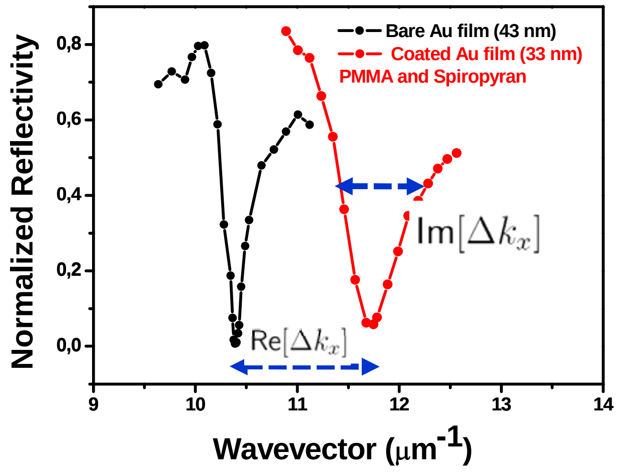
(Almost) all there is to know about plasmons in 3 curves

The reflectivity curve can be approximated as a Lorentzian

$$R = 1 - \frac{4\Gamma_i \Gamma_{rad}}{[k_x - (k_{spp})]^2 + [\Gamma_i + \Gamma_{rad}]^2}$$

$$k_{spp} = \frac{\omega}{c}\left(\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}\right)^{1/2} \pm \Delta k_x = k_x^0 \pm \Delta k_x$$

$$\Delta k_x = \left[\frac{\omega}{c}\frac{2}{(1+|\varepsilon_1|)}\left(\frac{|\varepsilon_1|}{|\varepsilon_1|-1}\right)^{3/2} \exp(-2|k_x^0|d_1)\right] r_{01}^p(k_x^0)$$



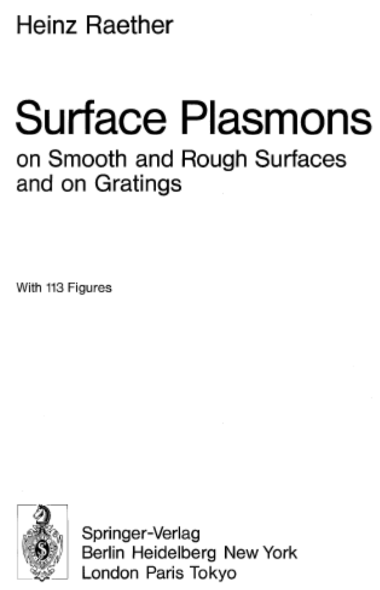
- Shift of the resonance:

$$\text{Re}[\Delta k_x] = \text{constant}.\text{Re}[r_{01}^p(k_x^0)]$$

- Damping of the resonance (roughness scattering can be negligible):

Radiative losses: $\Gamma_{rad} = \text{Im}[\Delta k_x] = \text{constant}.\text{Im}[r_{01}^p(k_x^0)]$

Intrinsic losses: $\Gamma_i = \text{Im}[k_x^0]$


Heinz Raether

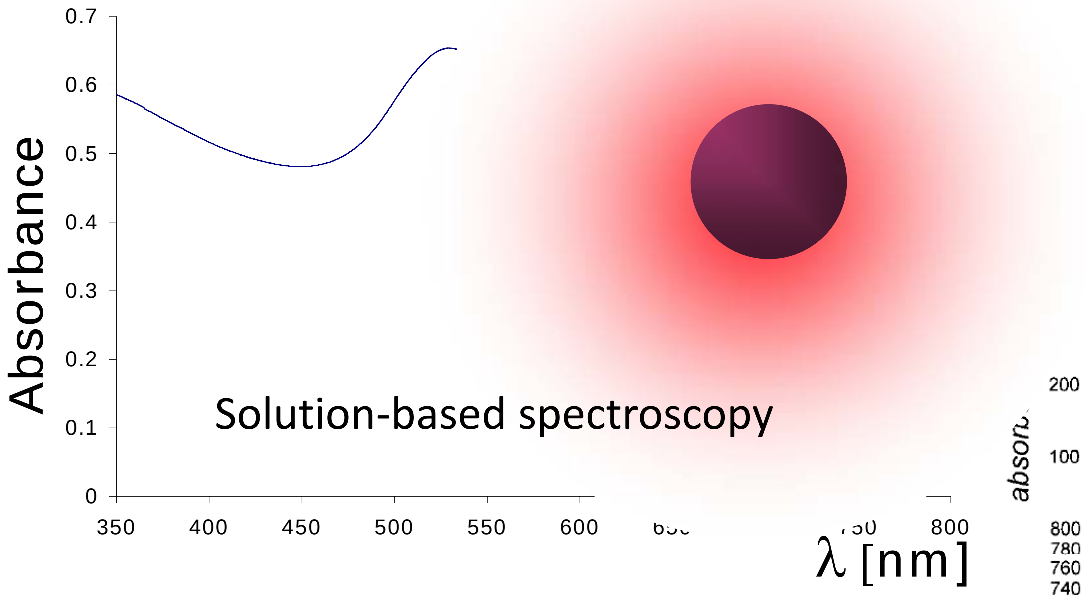
Surface Plasmons
on Smooth and Rough Surfaces
and on Gratings

With 113 Figures

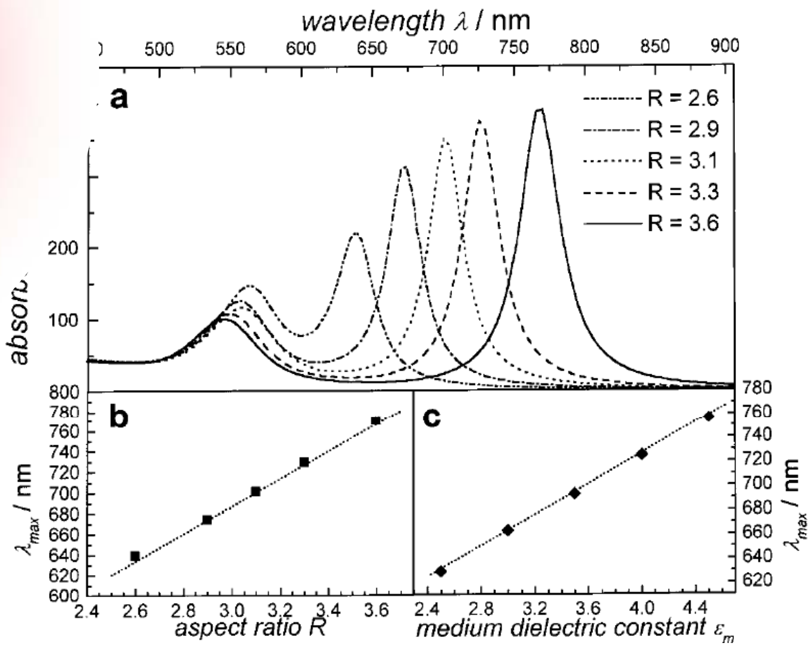
Springer-Verlag
Berlin Heidelberg New York
London Paris Tokyo

(Almost) all there is to know about plasmons in 3 curves

2 **Extinction spectroscopy**



Solution-based spectroscopy



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

(Almost) all there is to know about plasmons in 3 curves

Mie theory

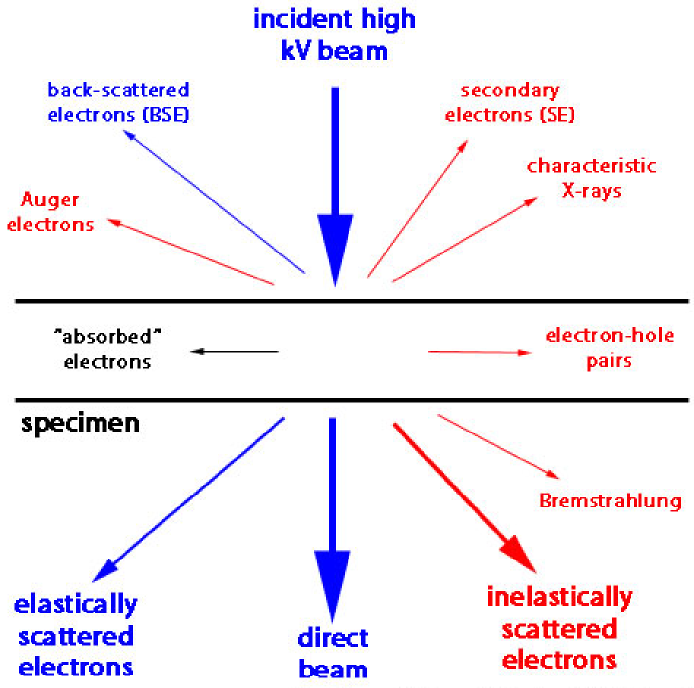
$$C_{abs} = \frac{6\pi V}{\lambda} \frac{3\epsilon_m^{''}}{(\epsilon_m^{'}+2)^2+\epsilon_m^{''2}}$$

Bohren & Huffman, *Absorption and Scattering of Light by Small Particles*, Wiley Inter Science

- Fröhlich frequency: $\omega_f \Rightarrow \epsilon_m^{'} = -2$
- Size correction $\omega_f \Rightarrow \epsilon_m^{'} = -2 + \beta(\frac{2\pi n a}{\lambda})^2$
- Surface polarization responsible for the field enhancement effect $\mathbf{E} = 4\pi \mathbf{a}^3 \frac{\epsilon_m - 1}{\epsilon_m + 2} \mathbf{E_o} + \mathbf{E_o}$
- Life time of the plasmon (dephasing time T2) $\tau_{sp} = T2/2 = \hbar/\Gamma$

(Almost) all there is to know about plasmons in 3 curves

3 **Electron energie-loss spectroscopy (EELS)**



modified from Williams & Carter (1996) Fig. 1.3

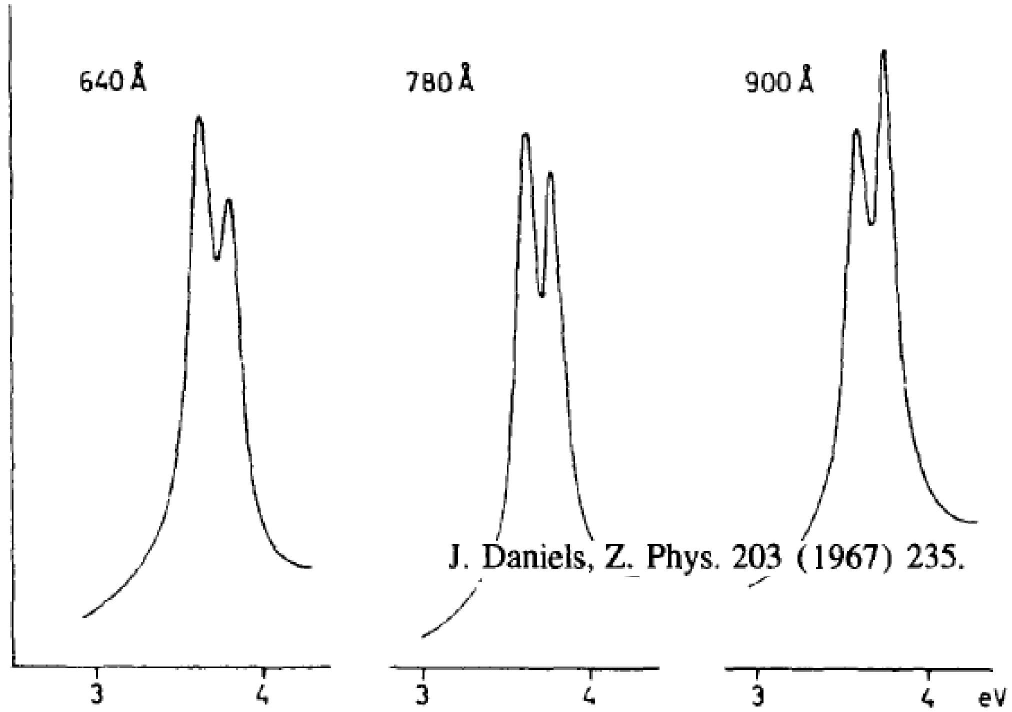
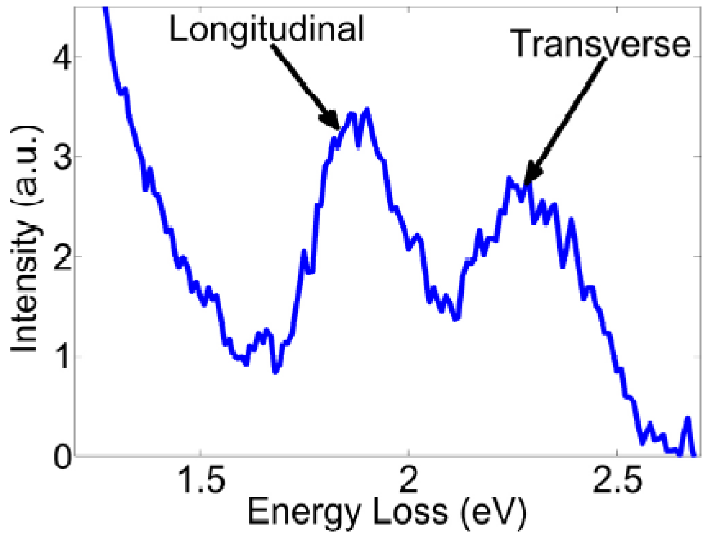


Fig. 5. EEL spectrum recorded with swift electrons (E_i = 50 keV) for thin Ag foils of different thickness at room temperature. Bulk and surface plasmons are clearly resolved, at $\hbar\omega_p$ = 3.78 eV and $\hbar\omega_{sp}$ = 3.63 eV as $\epsilon_2(\omega)$ nearly vanishes in this frequency range (from Ref. [65], used with permission).

(Almost) all there is to know about plasmons in 3 curves



M. N'Gom & T. B. Norris, *The emerging frontier at the intersection of optics and electron microscopy,* SPIE Newsroom, 10.1117/2.1200901.1493

• <u>Peaks in the EELS spectrum:</u>

$$[\mathrm{Im}(1/\varepsilon)]^{max} \text{ (bulk)}$$

$$[\mathrm{Im}(1/(\varepsilon+1))]^{max} \text{ (surface)}$$

• Measure of the <u>resonances</u> (bulk, localized, surface)

• Measure of the <u>relation dispersion</u> at large wave-vectors (electron momentum) by momentum-resolved EELS

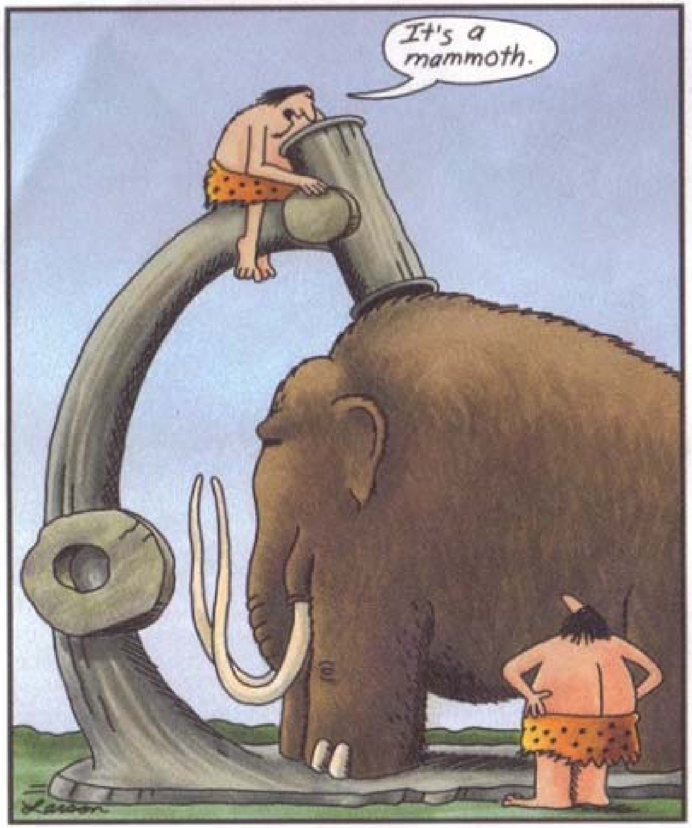
Why the heck do we want to image surface plasmons?

With imaging comes control!

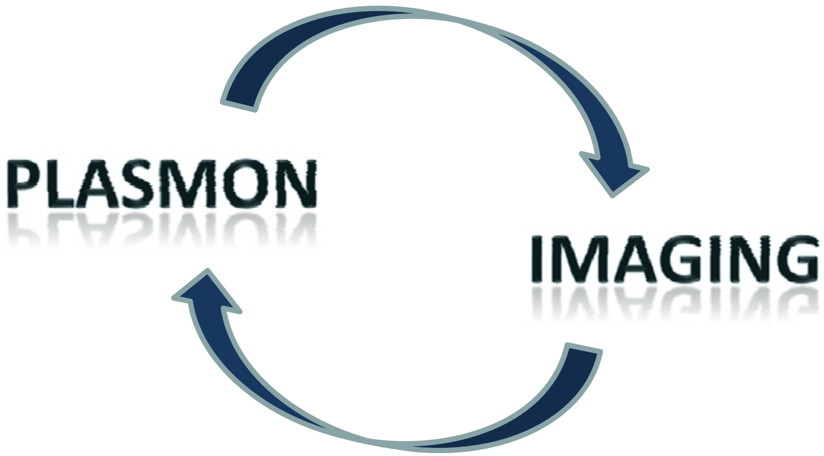
- Control over the propagation (plasmonic circuitry)
- Control over the localization (active substrates)

(the rebirth of plasmonics was partially triggered by our ability to visualize surface plasmons)

Surface plasmon and imaging: an ambivalence



Early microscope



Plasmon's principal imaging characteristics

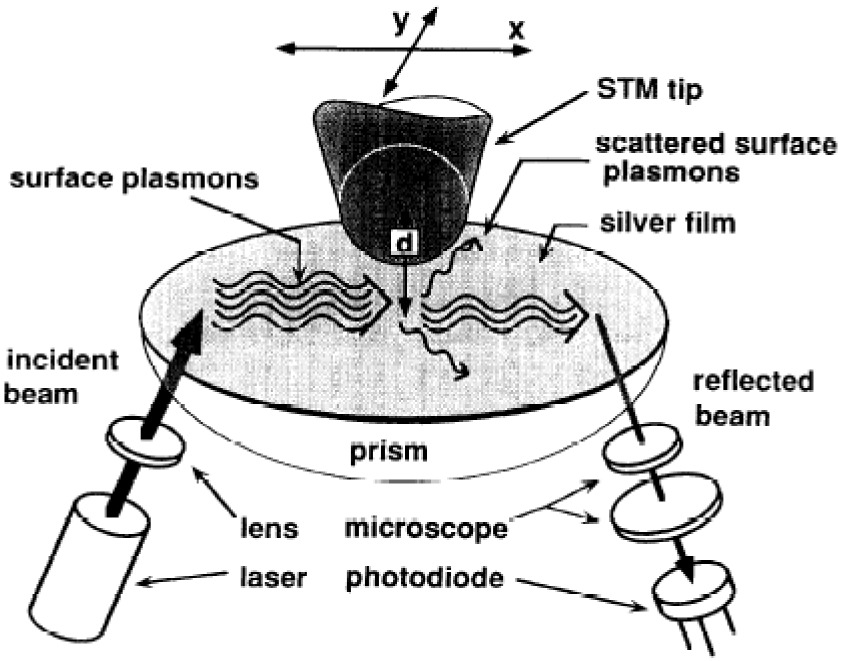
• Surface plasmons are **evanescent** waves confined at a **surface**	**Near-field microscopy**
• Surface plasmons can be **leaky**	**Leakage microscopy**
• Surface plasmons can **interact** with molecules	**Fluorescence microscopy**
• Localized surface plasmons can be scattered	**Dark-field microscopy** **Cathodoluminescence**
• Surface plasmons can induce **non-linear** phenomena	**Confocal microscopy** **Photoelectron microscopy**
• Surface plasmons are **loss** channel for e^-	**STEM EELS**
• Surface plasmons can trigger photochemical reactions	**Photochemical imaging**

1992: the plasmon microscope

VOLUME 68, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JANUARY 1992

Scanning Plasmon Near-Field Microscope

M. Specht, J. D. Pedarnig, W. M. Heckl, and T. W. Hänsch
Sektion Physik der Universität München, Schellingstrasse 4/III, D-8000 München 40, Germany



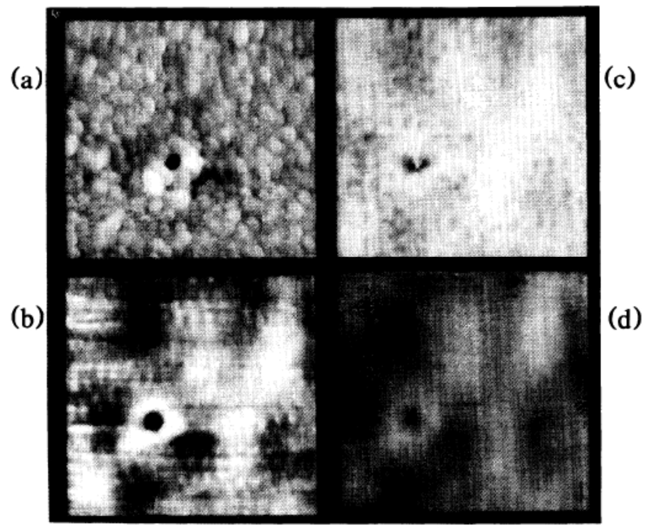
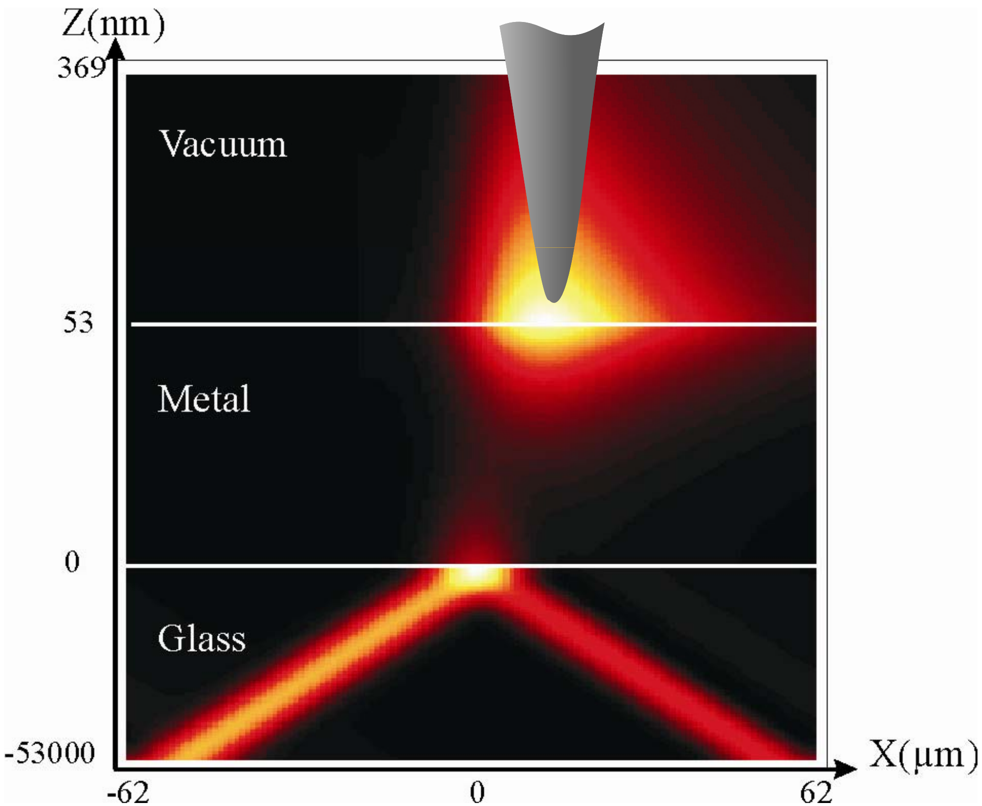


FIG. 2. (a) STM image taken at a 600 nm×600 nm area on a silver surface (tip-sample spacing below 1 nm); (b),(c) SPNM images taken at the same area (tip-sample spacing 3 and 10 nm, respectively; wavelength 632.8 nm); (d) image recorded in the "STM-SPNM hybrid mode" (tip-sample spacing below 1 nm).

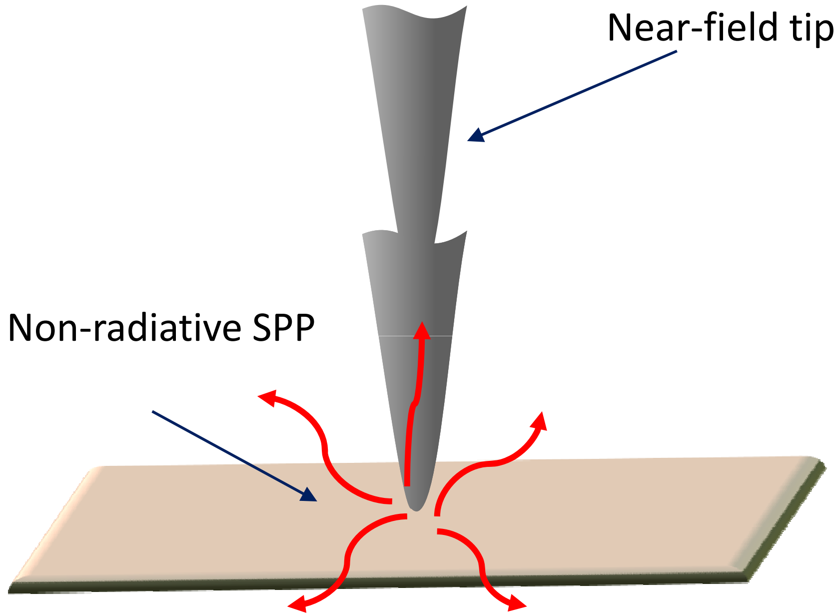
NEAR-FIELD OPTICAL MICROSCOPY

(the rebirth of plasmonics)

Principle of near-field microscopy in the context



Intensity distribution of the plasmon field excited by Kretschmann configuration, Courtesy of Prof. F. Baida, FEMTO-ST, Besançon-France



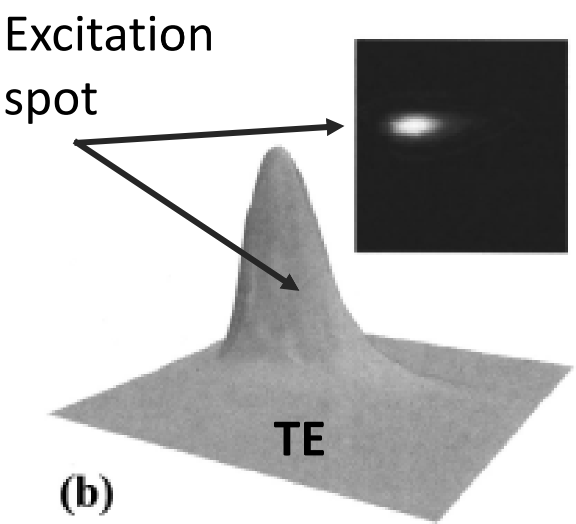
Requirement: for a imaging a thin-film SPP, the spatial extend of the SPP > the excitation area (local excitation)

Near-field microscopy: the first glance at a plasmon

VOLUME 72, NUMBER 18 PHYSICAL REVIEW LETTERS 2 MAY 1994

Imaging of Surface Plasmon Propagation and Edge Interaction Using a Photon Scanning Tunneling Microscope

P. Dawson,[1] F. de Fornel,[2] and J-P. Goudonnet[2]
[1]*Department of Pure and Applied Physics, Queen's University of Belfast, Belfast BT7 1NN, United Kingdom*
[2]*Faculté Sciences Mirande, Laboratoire Physique du Solide, Equipe Optique Submicronique, Université de Bourgogne, BP 138, 21004 Dijon Cedex, France*



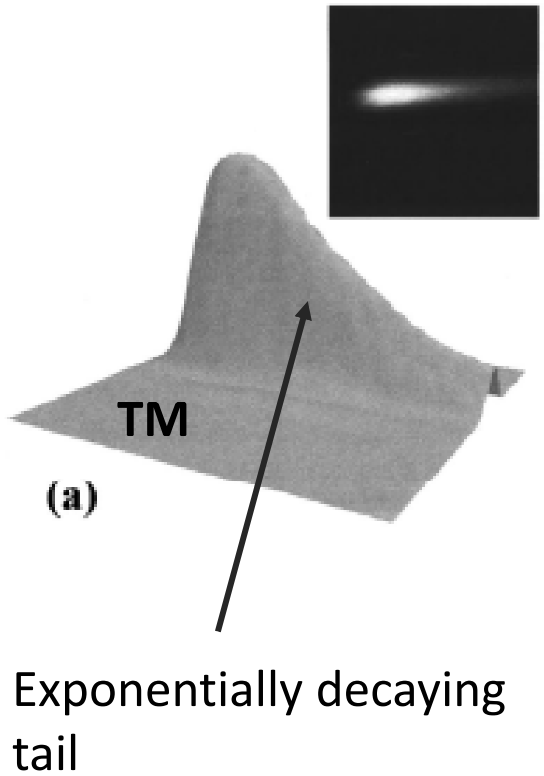
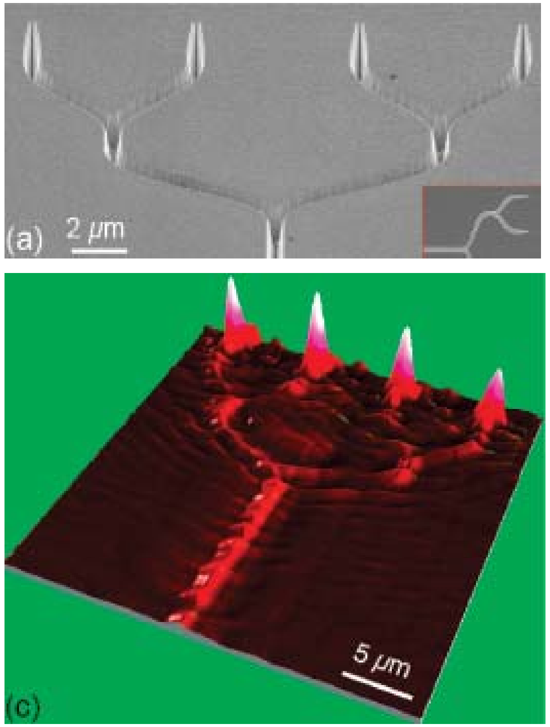


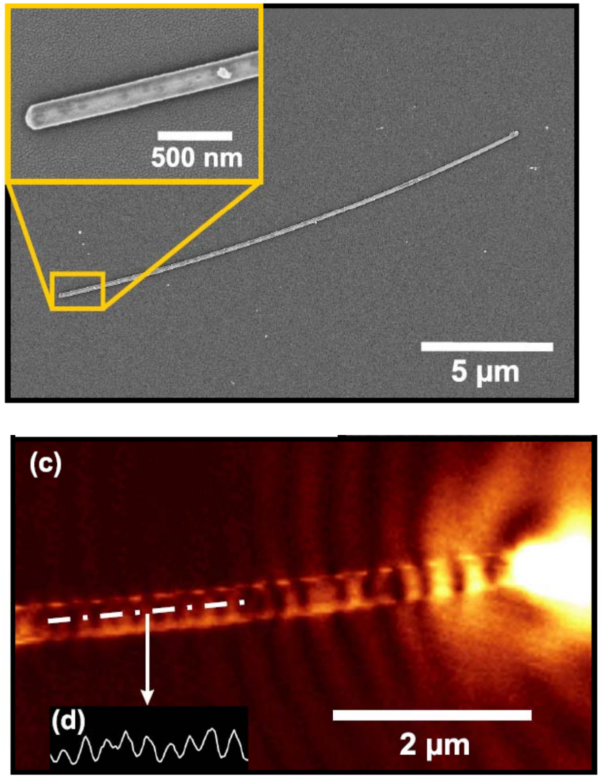
FIG. 5. PSTM images of SPP propagating (left to right) from a localized launch site at $\lambda_1 = 632.8$ nm, the triangular coupling prism used in the setup is shown in Fig. 1. The scan range is 36×36 μm and insets show two-dimensional views of images. (a) Sample $B1$; measured $1/e$ propagation length is 13.8 μm. (b) Sample $B3$; measured $1/e$ propagation length is 4.9 μm.

Understanding SPP propagation and interactions

SPP waveguides (here V-grooves and nanowires)



V. Volkov et al., *Nano. Lett.,*ASAP (2009)

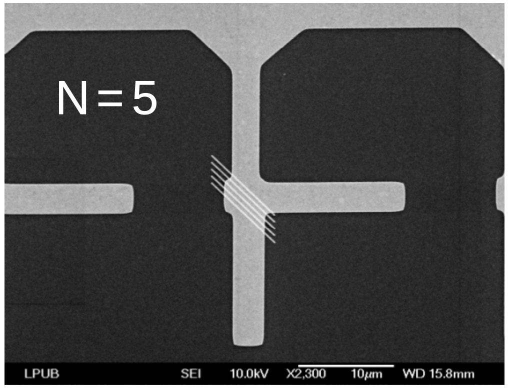


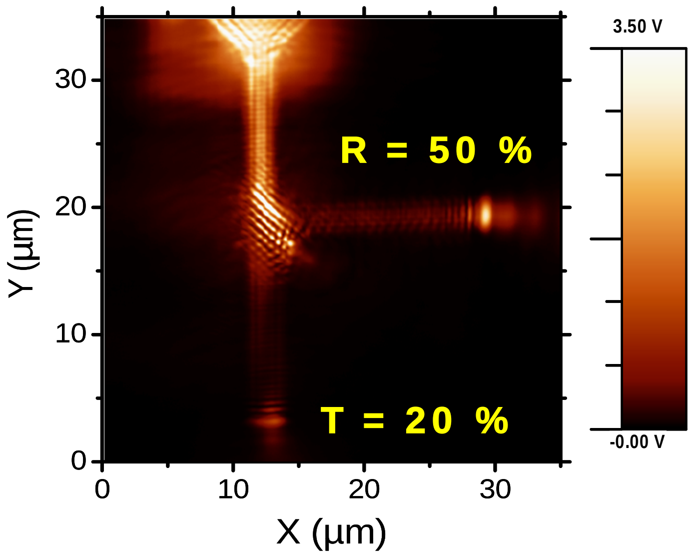
H. Ditlbacher et al., *Phys. Rev. Lett.* , 95, 257403 (2005)

Here, near-field imaging enabled the demonstration of true-subwavelength propagation in nanowaveguides

Understanding SPP propagation and interactions

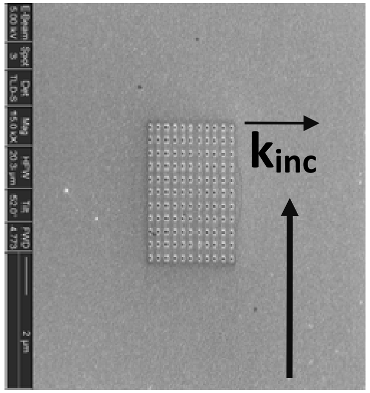
SPP splitters



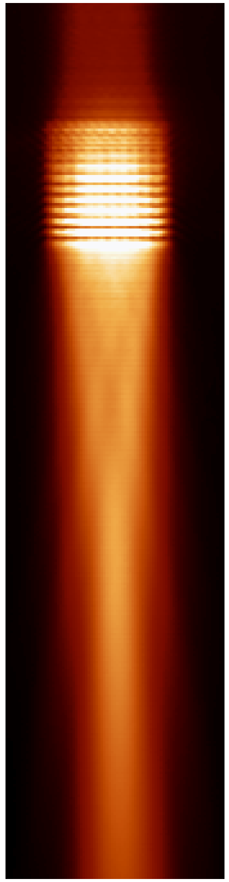


J-C Weeber, et al., *Appl. Phys. Lett.*,87, 221101 (2005)

SPP Launchers



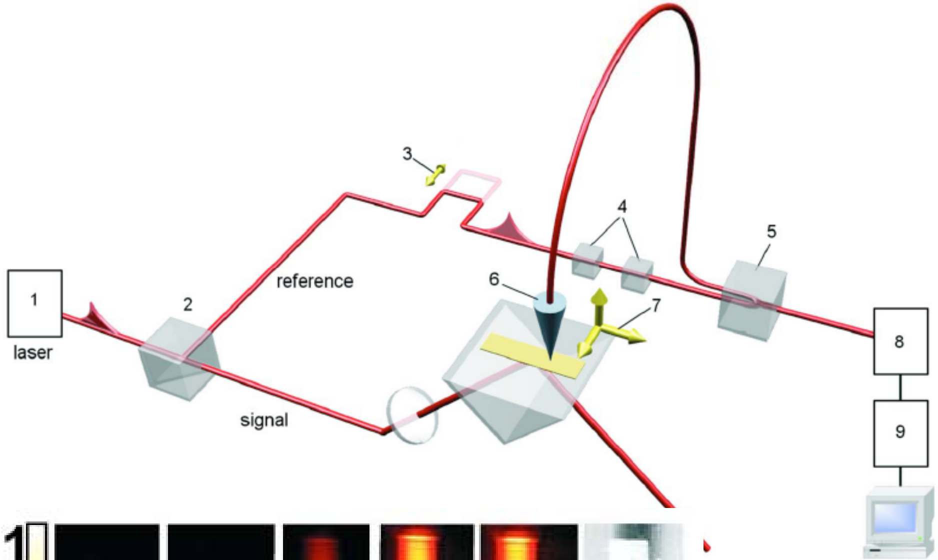
J-Y. Laluet, et al., *Appl. Phys. Lett.*,15, 3488 (2007)

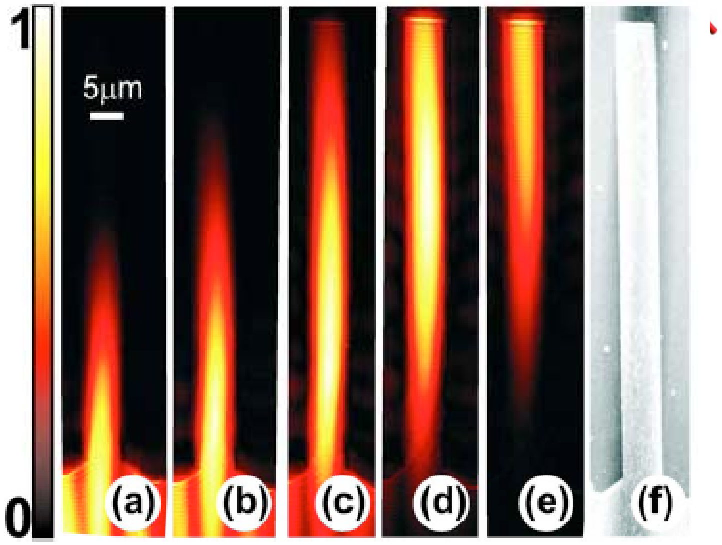


Control over the propagation with passive elements

Tracking SPP in space and time

Heretodyned detection





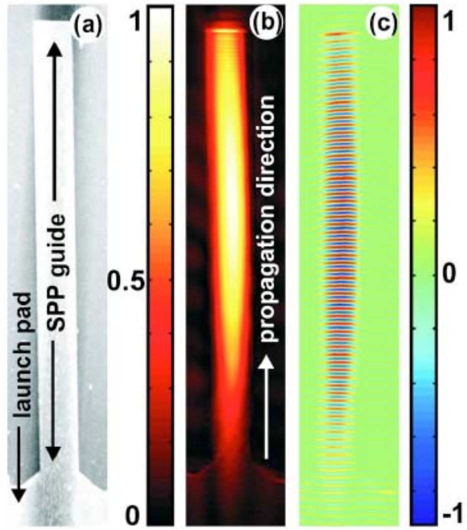


FIG. 8. (Color online) (a) Topography of the SPP waveguide obtained by shear-force feedback. It consists of a 55 nm thick Au guide, 6 μm wide and 80 μm long. (b) Normalized amplitude measurement of the E-field of the SPP wavepacket inside the 6 μm waveguide. (c) Combined phase and amplitude information [$\sim A\cos(\phi)$] of the same measurement as (b). Scan lines run from top to bottom and the scan frame is $15\times 110\ \mu m^2$, wavelength in air used to excite the SPPs: 1500 nm pulses with 20 nm bandwidth.

FIG. 9. (Color online) (a)–(e) Normalized amplitude information of the SPP wavepacket E-field. Succeeding frames are new scans of the probe. In between the frames the delay line is lengthened to 14.4 μm. Therefore, the time between two frames is 48 fs. The scan frame is $15\times 110\ \mu m^2$, scan lines run from top to bottom. (f) Topography of the SPP waveguide obtained by shear-force feedback.

M. Sandke et al., *Rev. Sci. Instr.* 79, 013704 (2008)

Looking a confined plasmons using near-field optics

APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 2 14 JULY 2003

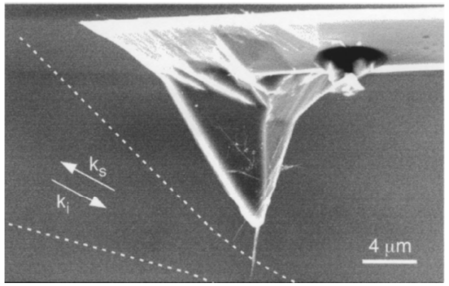
Coherent imaging of nanoscale plasmon patterns with a carbon nanotube optical probe

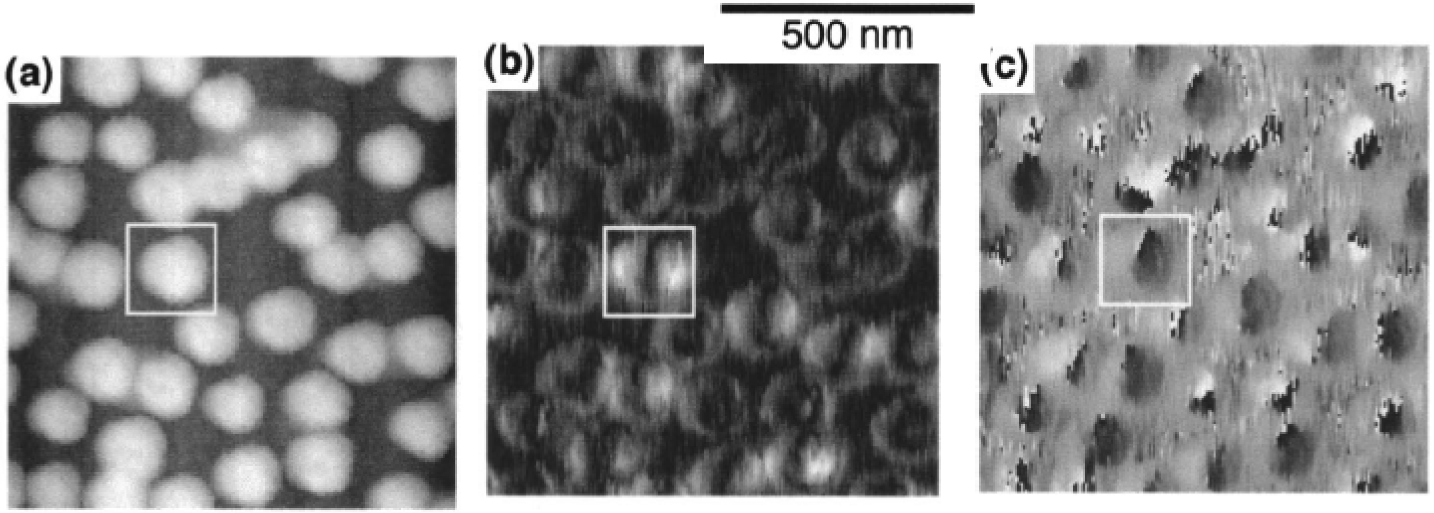
R. Hillenbrand[a)]
Nano-Photonics Group, Max-Planck-Institut für Biochemie, 82152 Martinsried, Germany

F. Keilmann
Abteilung Molekulare Strukturbiologie, Max-Planck-Institut für Biochemie, 82152 Martinsried, Germany

P. Hanarp and D. S. Sutherland
Department of Applied Physics, Chalmers University of Technology, 41296 Göteborg, Sweden

J. Aizpurua
National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8423





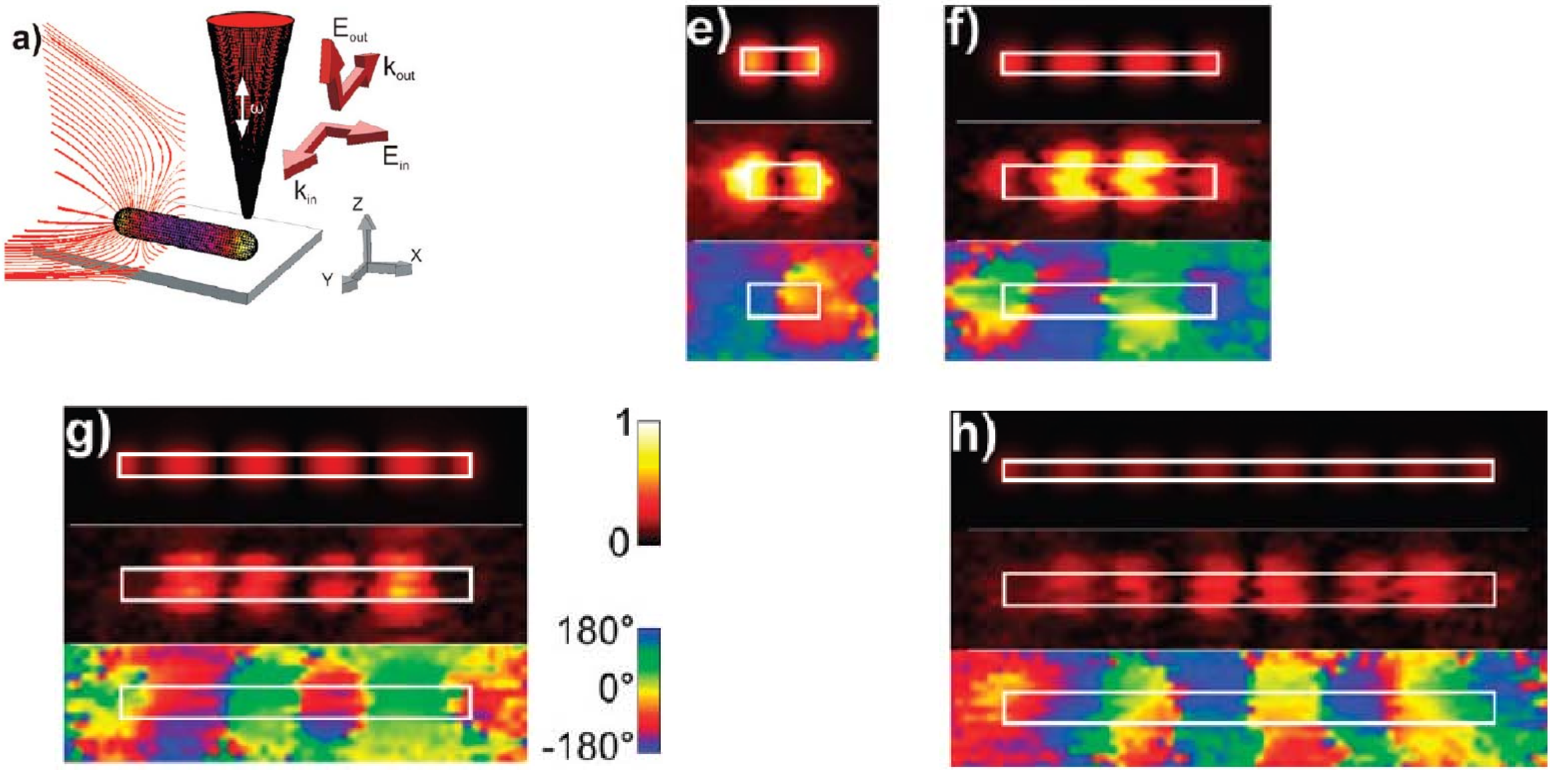
Localized SPP have dipolar-like distribution (amplitude and phase)

Looking a confined plasmons using near-field optics

Fabry-Pérot Resonances in One-Dimensional Plasmonic Nanostructures

NANO LETTERS
2009
Vol. 9, No. 6
2372-2377

Jens Dorfmüller,[*,†] Ralf Vogelgesang,[*,†] R. Thomas Weitz,[†] Carsten Rockstuhl,[‡] Christoph Etrich,[¶] Thomas Pertsch,[¶] Falk Lederer,[‡] and Klaus Kern[†,§]



Pro et contra of near-field imaging

Resolution (still) strongly depends on tip quality

Complex measurements

Perturbative

Access to the bound E.M. field

Spectroscopic data

Space and time investigations

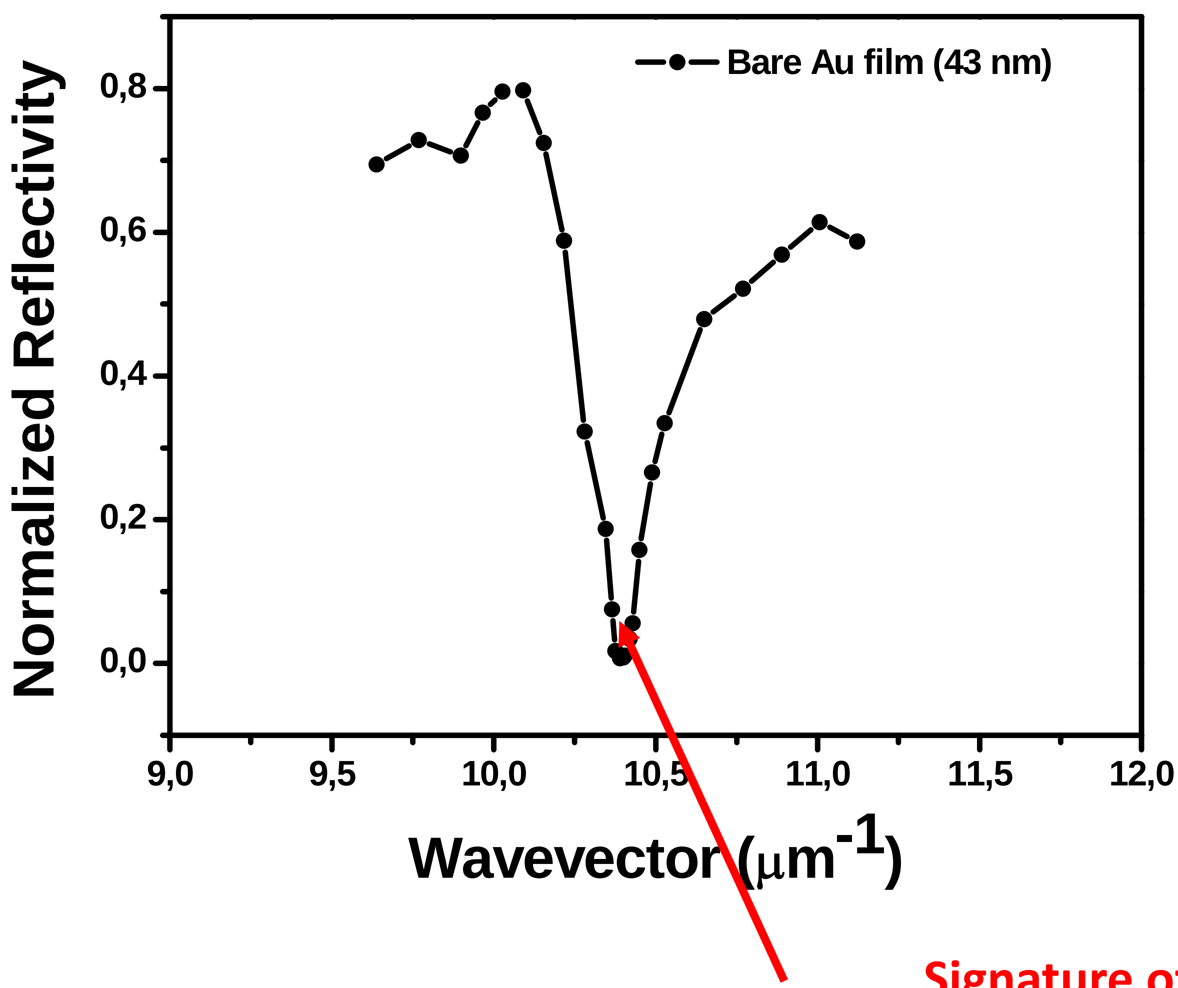
Flexible with sample requirements

Phase measurement

LEAKAGE RADIATION MICROSCOPY

(naked-eye plasmons)

Hand-wavy argument

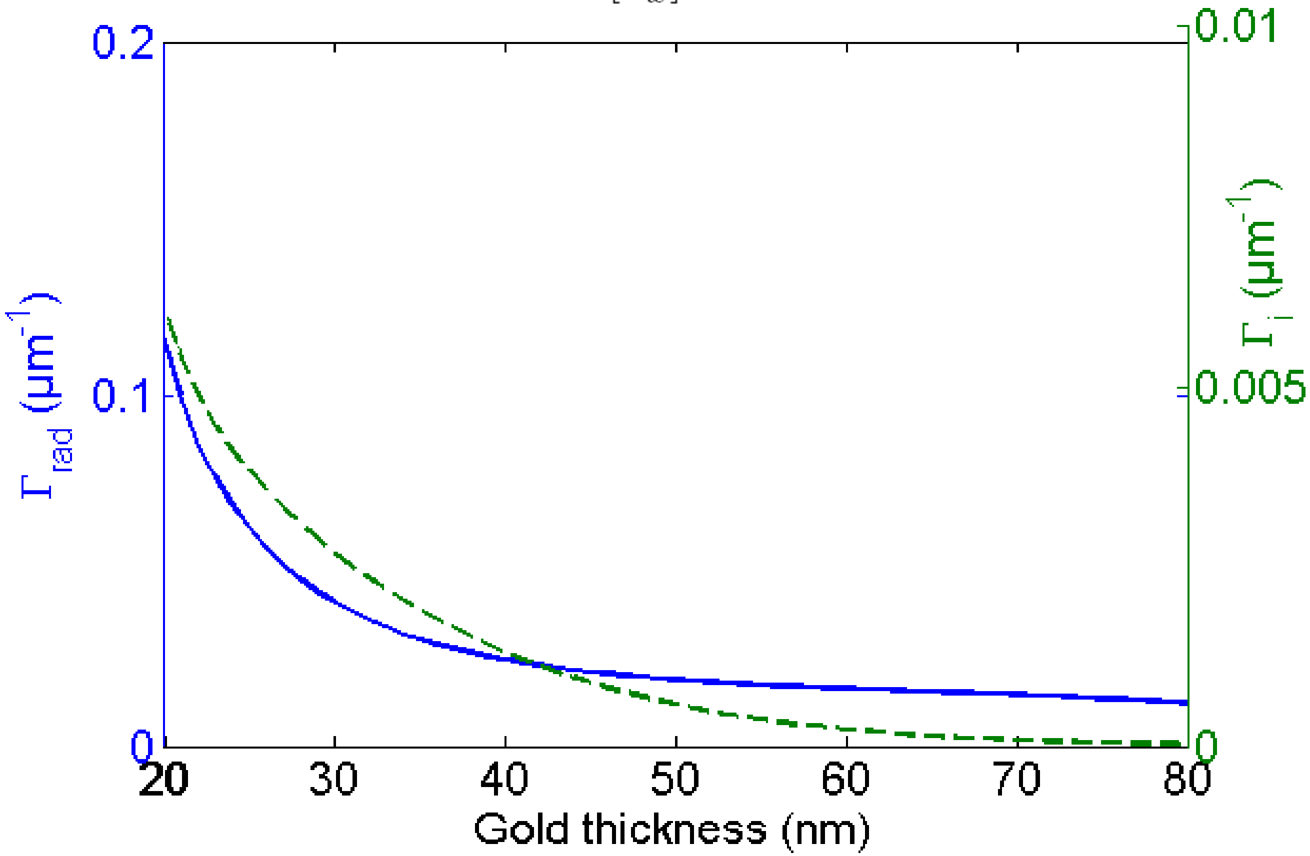


Signature of the SP; the incident energy is coupled to the plasmon

Hand-wavy argument

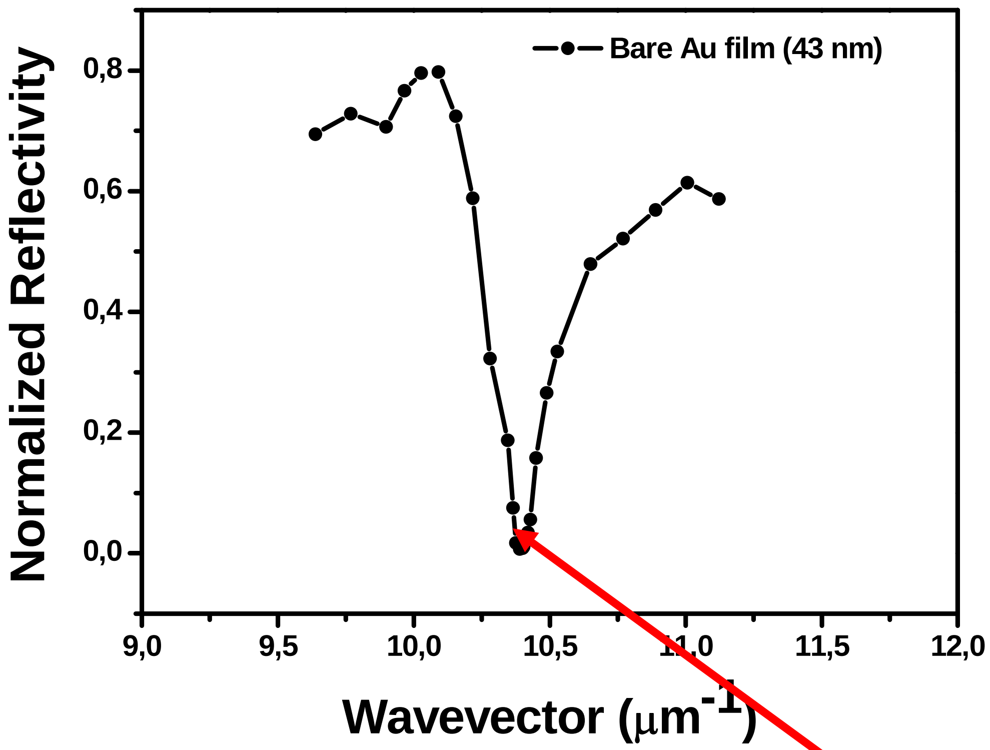
Radiative losses: $\Gamma_{rad} = \text{Im}[\Delta k_x] = \text{constant.Im}[r^p_{01}(k^0_x)]$

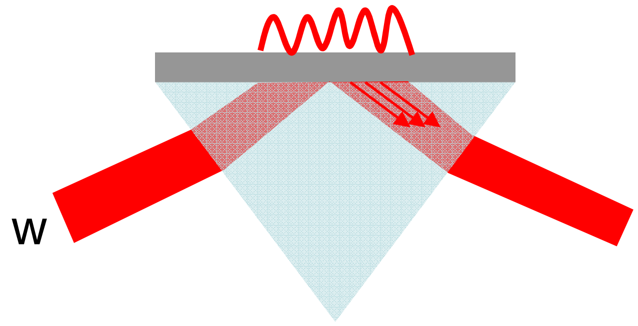
Intrinsic losses: $\Gamma_i = \text{Im}[k^0_x]$



J. Grandidier, PhD thesis 2009, Université de Bourgogne

Hand-wavy argument



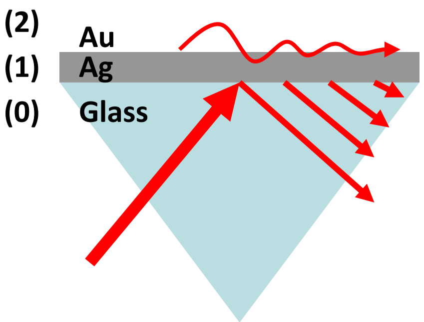


Finite-size beam (w=mm)>> SPP attenuation length

Signature of the SP; leakage radiation are interfering destructively with reflected beam

T+R+A=1 T=R=0 ⟶ A=1

Rigorous basis



$$k_{zo} = \left(\varepsilon_o \left(\frac{\omega}{c}\right)^2 - k_x^2\right)^{1/2}$$

$$k_{z1} = \left(\varepsilon_1 \left(\frac{\omega}{c}\right)^2 - k_x^2\right)^{1/2}$$

$$k_{z2} = \left(\varepsilon_2 \left(\frac{\omega}{c}\right)^2 - k_x^2\right)^{1/2}$$

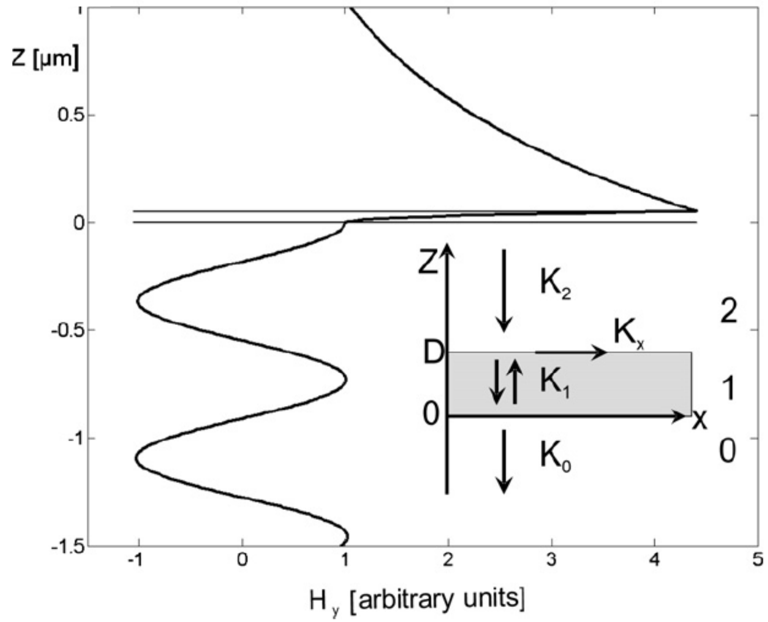
$$k_x = k_{spp} = \sqrt{\varepsilon_o}\frac{\omega}{c}\sin\theta$$

$$k_{spp} = \frac{\omega}{c}\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1 + \varepsilon_2}\right)^{1/2}$$

$$k_{z2} = \left(\frac{\omega}{c}\right)\sqrt{\left(\varepsilon_2 - \varepsilon_o \sin^2\theta\right)}$$ inhomogeneous wave

$$k_{z1} = \left(\frac{\omega}{c}\right)\sqrt{\left(\varepsilon_1 - \varepsilon_o \sin^2\theta\right)}$$ inhomogeneous wave

$$k_{zo} = \sqrt{\varepsilon_o}\left(\frac{\omega}{c}\right)\sqrt{(1 - \sin^2\theta)}$$ homogeneous wave



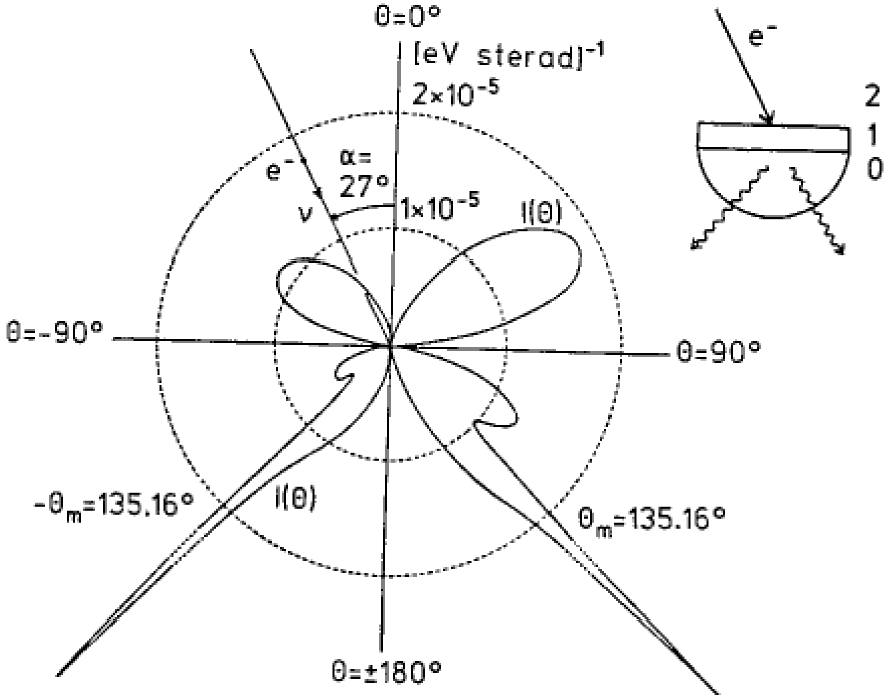
A. Drezet et al., *Mat. Sci. Eng. B* 149, 220 (2008)

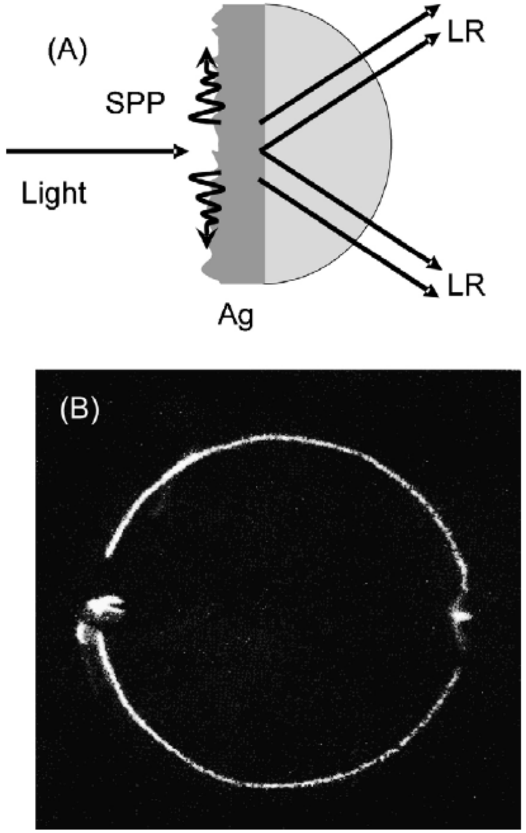
First measurements

Z. Physik 244, 1–5 (1971)

Light Emission from Non Radiative Plasmons Excited by Electrons on Smooth Surfaces

E. Kröger and H. Raether
Institut für Angewandte Physik der Universität Hamburg





Simon & J.K. Guha, *Opt. Comm.*, 18, 391 (1976)
A. Drezet et al., *Mat. Sci. Eng. B.* 149, 220 (2008)

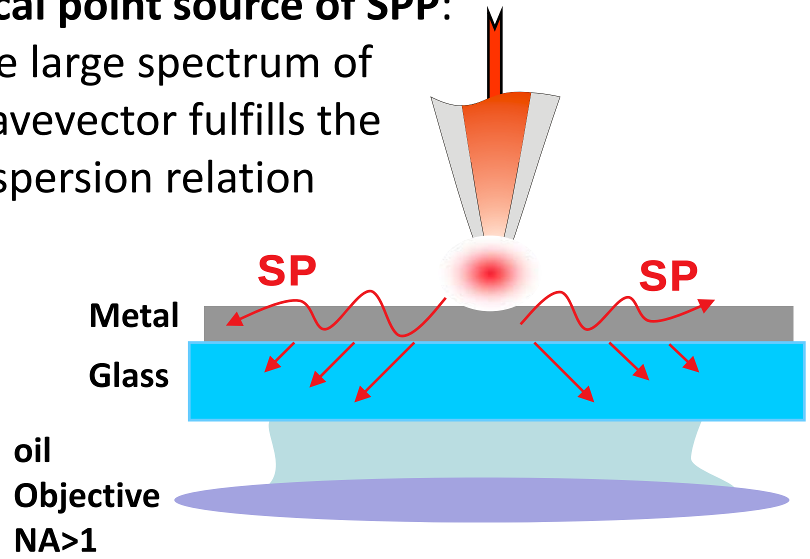
Two-dimensional mapping of SPP by LRM

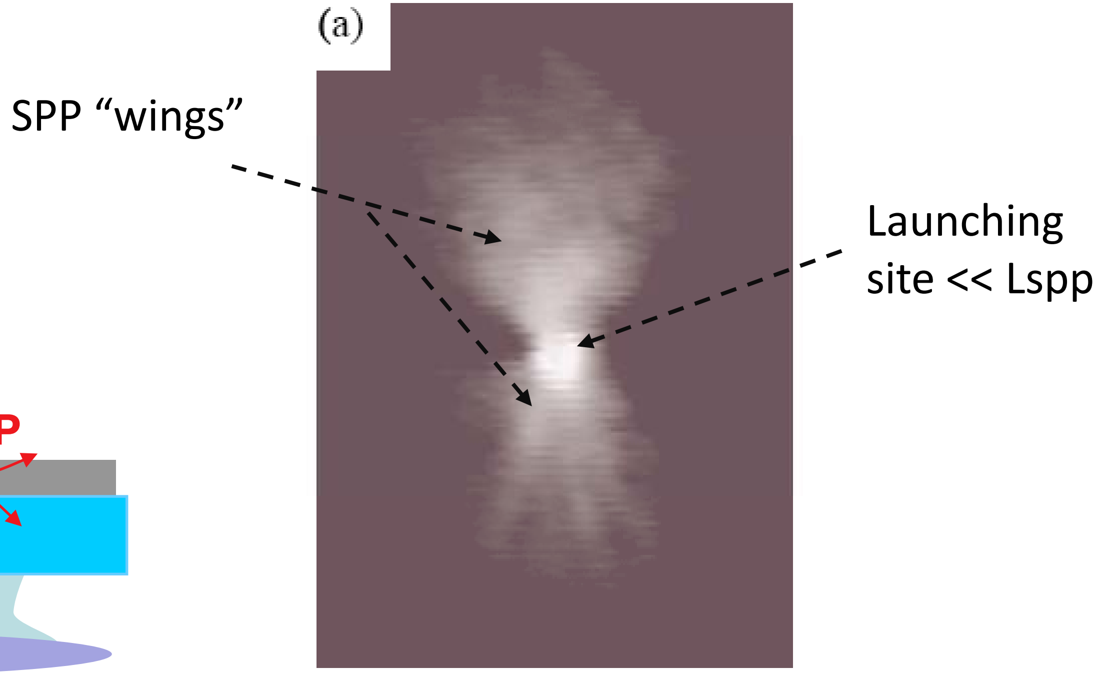
VOLUME 77, NUMBER 9 PHYSICAL REVIEW LETTERS 26 AUGUST 1996

Local Excitation, Scattering, and Interference of Surface Plasmons

B. Hecht,[1] H. Bielefeldt,[1] L. Novotny,[2] Y. Inouye,[1,*] and D. W. Pohl[1,†]
[1] *IBM Research Division, Zurich Research Laboratory, CH-8803 Rüschlikon, Switzerland*
[2] *Swiss Federal Institute of Technology, Eidgenössische Technische Hochschule Zürich, CH-8092 Zurich, Switzerland*
(Received 14 December 1995; revised manuscript received 29 March 1996)

The near-field tip acts as a **local point source of SPP**: the large spectrum of wavevector fulfills the dispersion relation





Imaging SPP interactions

PHYSICAL REVIEW B, VOLUME 63, 155404

Plasmon optics of structured silver films

A. Bouhelier,* Th. Huser,† H. Tamaru,‡ H.-J. Güntherodt, and D. W. Pohl
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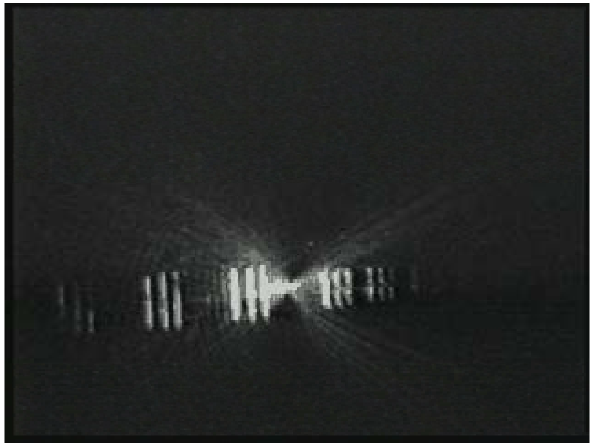
Fadi I. Baida and D. Van Labeke
Laboratoire d'Optique PM Duffieux, CNRS UMR 6603, Institut des Microtechniques de Franche-Comté, FR0067 CNRS, Université de Franche-Comté, F-25030 Besançon Cedex, France

The launch of a SPP

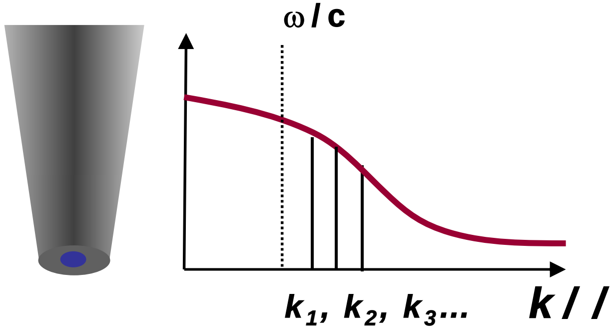
Polarization control



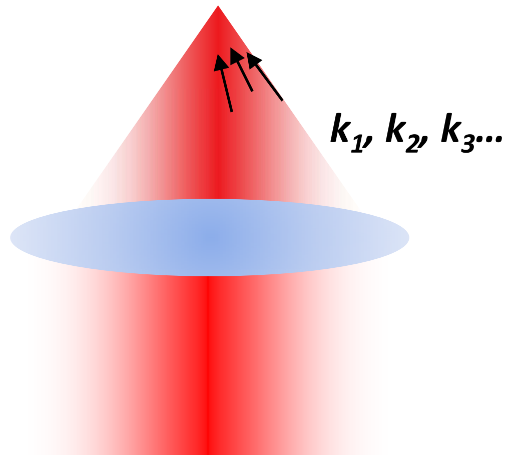
SPP interference

Going far-field (SPP imaging made easy)

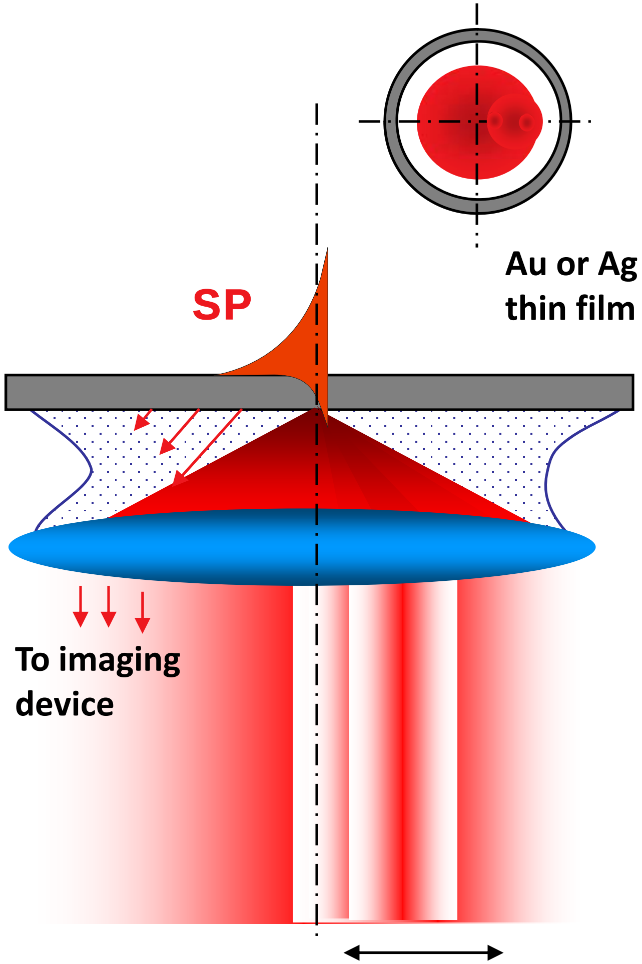
Near-field coupling



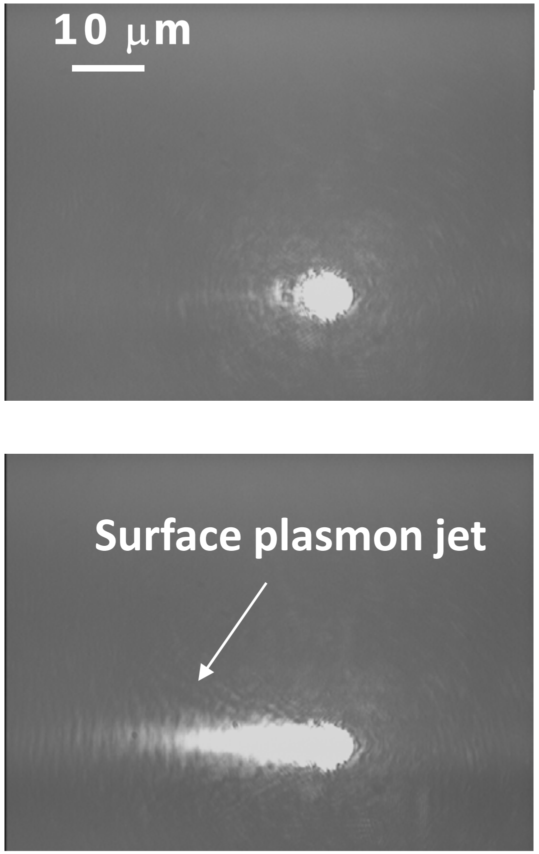
Focusing



Going far-field (SPP imaging made easy)



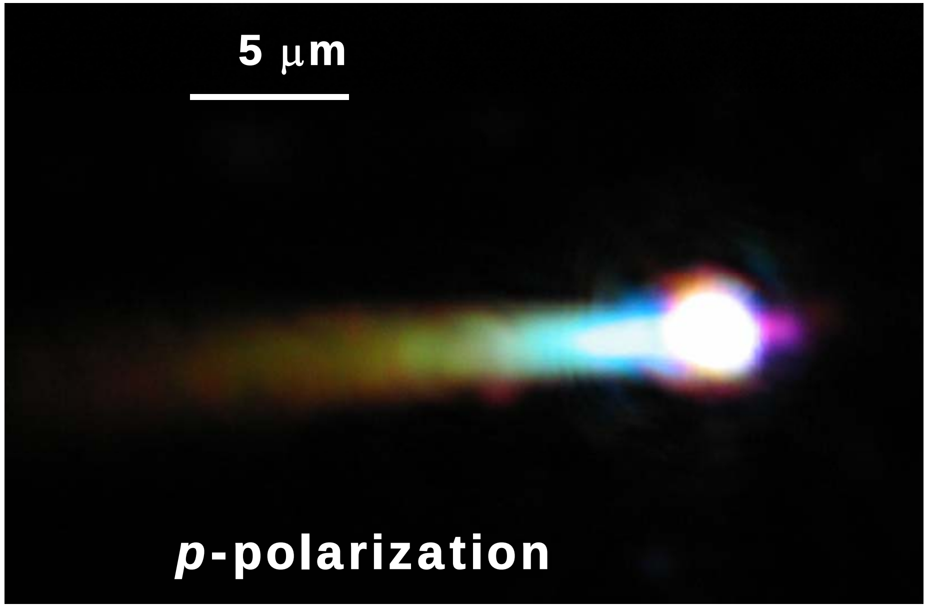
To be adjusted for
SP excitation (kspp)

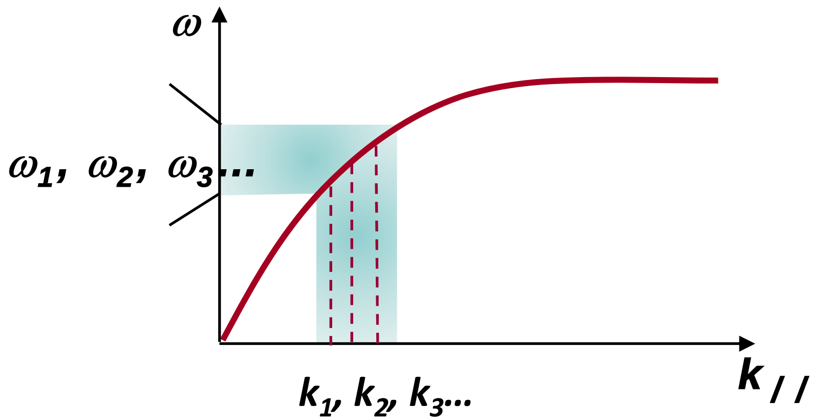


A. Bouhelier and G. P. Wiederrecht, *Opt. Lett.,* **30**, 884 (2005)
A. Hohenau et al, *Opt. Lett.,* **30**, 893 (2005)

Multicolor plasmon jet

- Broad-band surface plasmon excited from a white-light femtosecond laser source
- Color spread reflects the surface plasmon dispersion: group velocities (dω/dk) change with color



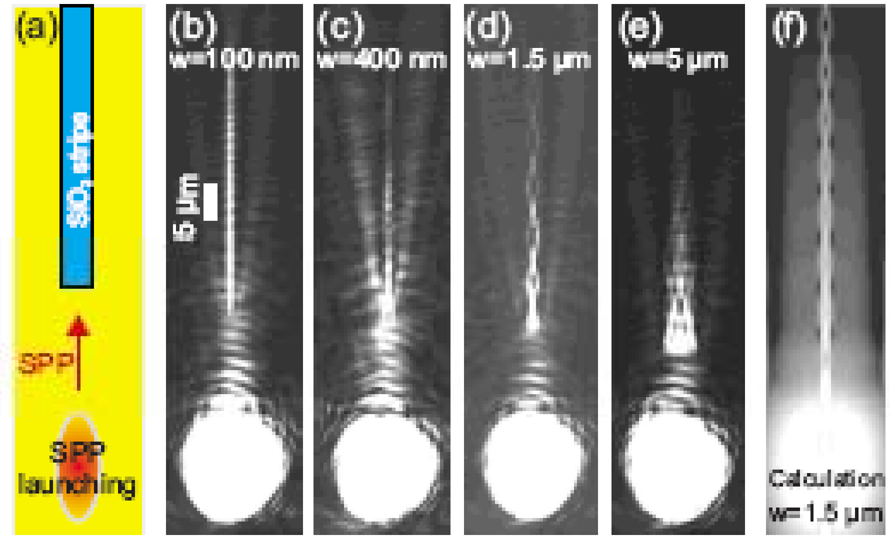


A. Bouhelier and G. P. Wiederrecht, Phys. Rev. B, 71, 195406 (2005)

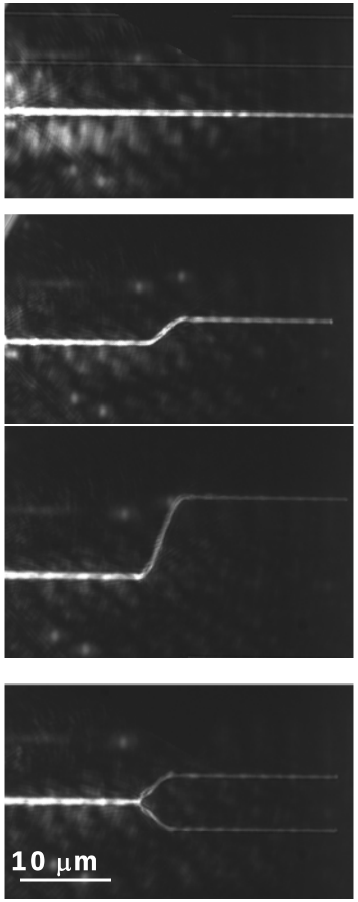
SPP waveguiding imaged by LRM

- Details of the propagation of SPP in waveguiding structures

Dielectric loaded SPP waveguide

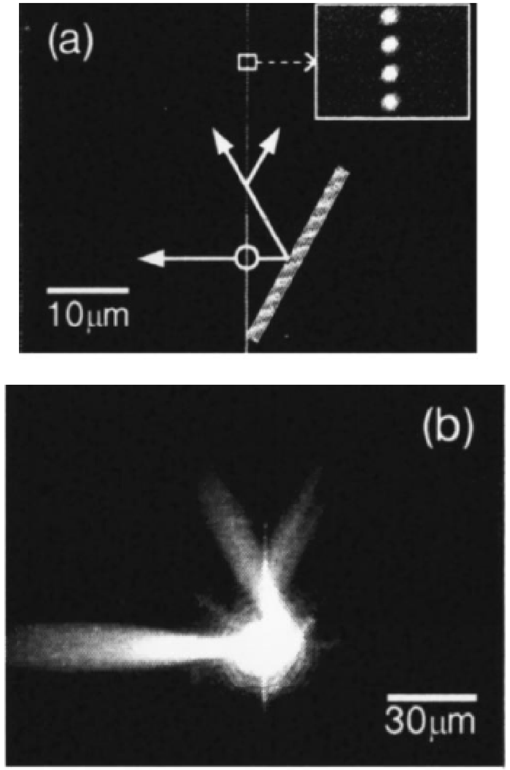


J. Grandidier et al, Phys. Rev. B, 78, 245419 (2008)

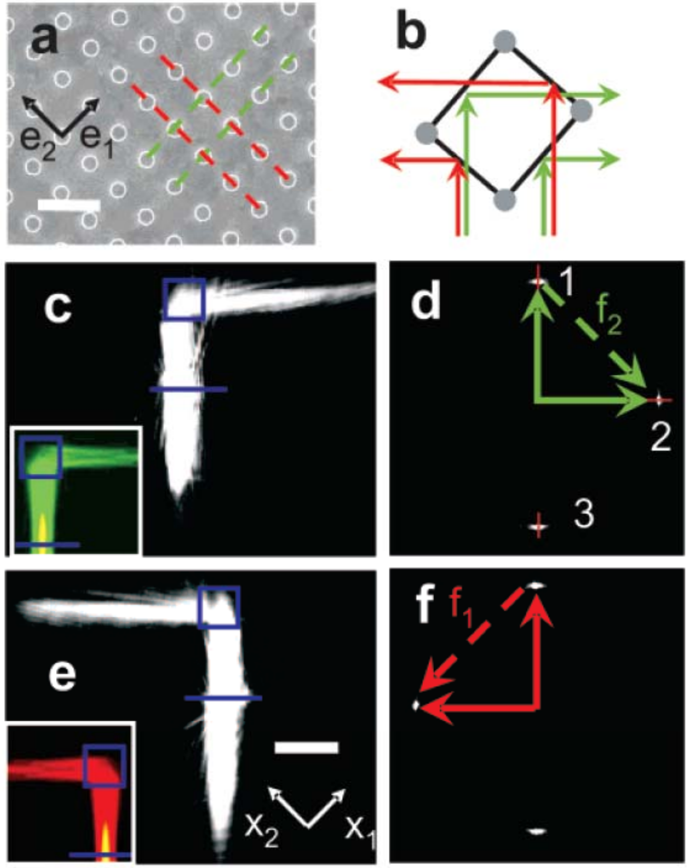


SPP control imaged by LRM

- Leakage radiation microscopy allows rapid prototyping of integrated plasmonic components



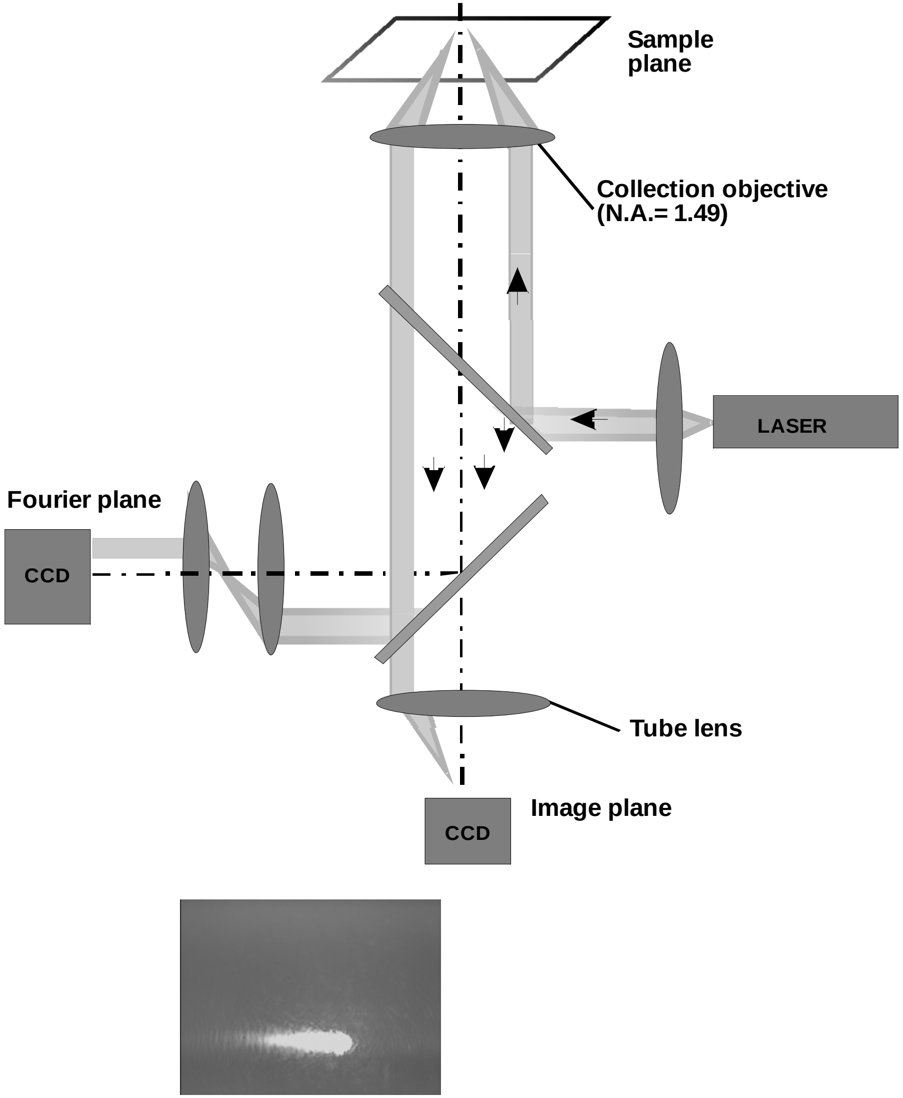
H. Ditlbacher et al, Appl. Phys. Lett. 81, 1762 (2002)



A. Drezet et al, Plasmonics B, 7, 1697 (2007)

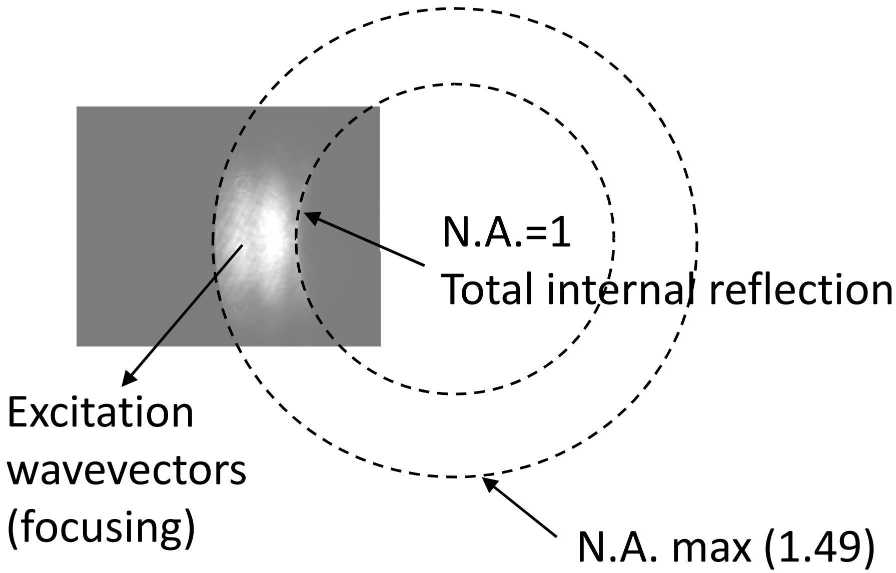
Beyond propagation: Fourier imaging

- Imaging the Fourier plane gives access to the reciprocal space (wave-vectors)



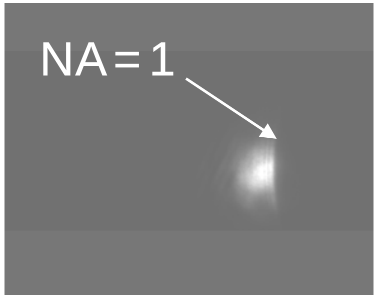
Imaging of the objective's back-aperture

(glass/air interface)

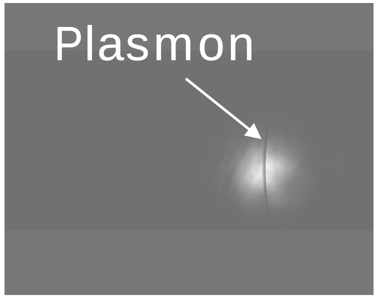


Beyond propagation: Fourier imaging

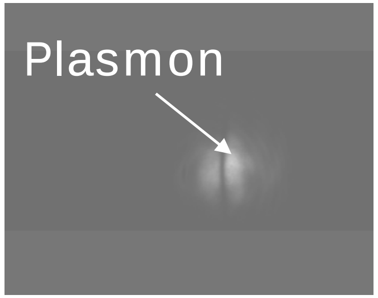
Glass/air interface

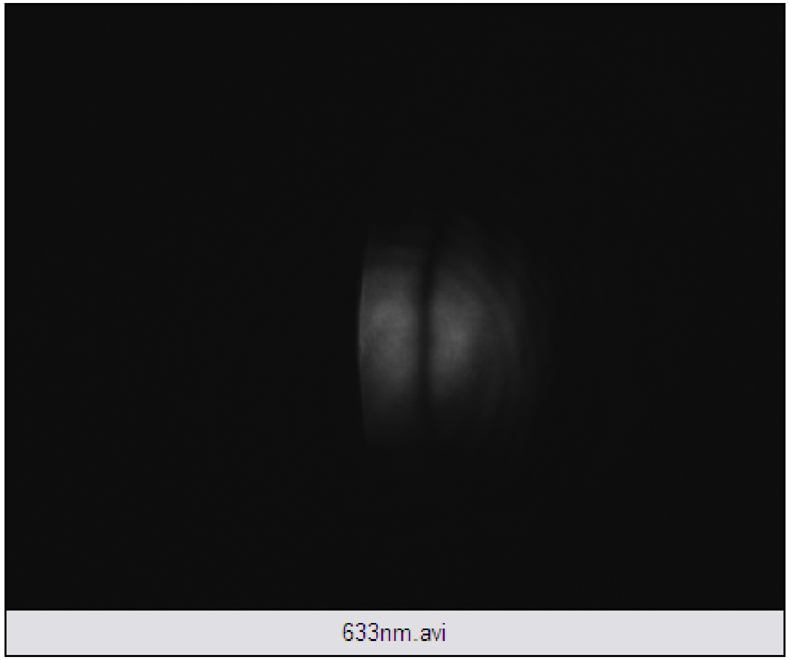


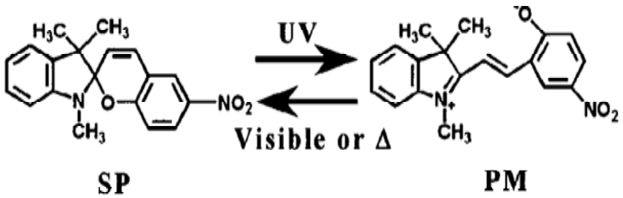
Glass/Ag/air interface



Glass/Ag/**Spiro**/air interface

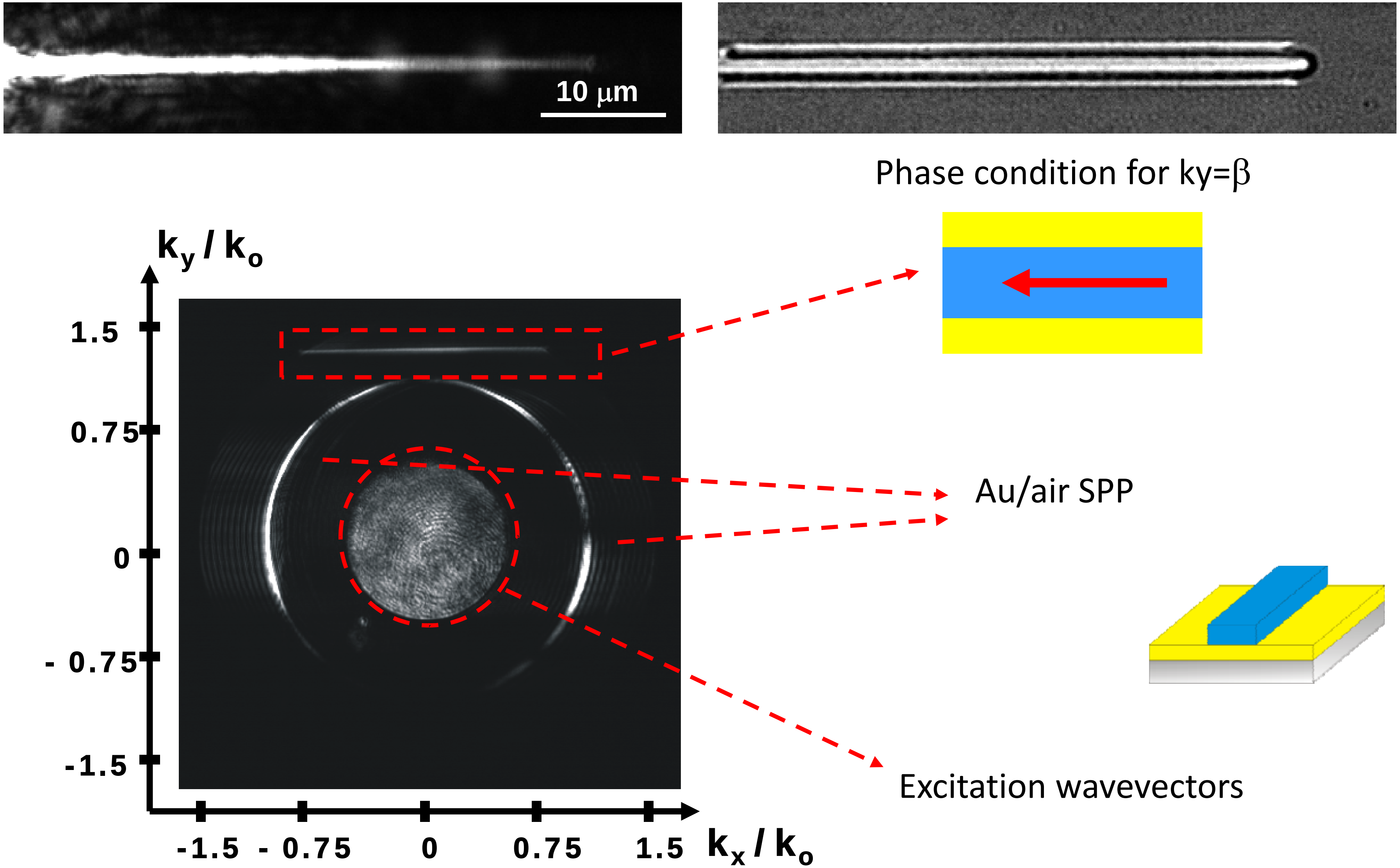






- Optical control of the resonant wavevectors through photochromism

Beyond propagation: Fourier imaging



S. Massenot et al., *Appl. Phys. Lett.* 91, 243102 (2008)

Pro et contras of Leakage Radiation Microscopy

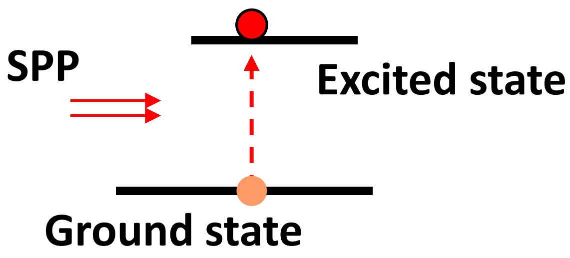
- Rapid two-dimensional mapping of SPP
- Multi-wavelength, multi-wavevectors
- Only needs an oil immersion objective
- Access to direct and reciprocal space

- Limited spatial resolution (diffraction)
- Restricted to leaky plasmons
- Limited to small effective indices (<1.5)

FLUORESCENCE MICROSCOPY

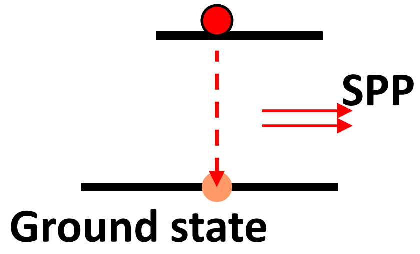
(glowing plasmons)

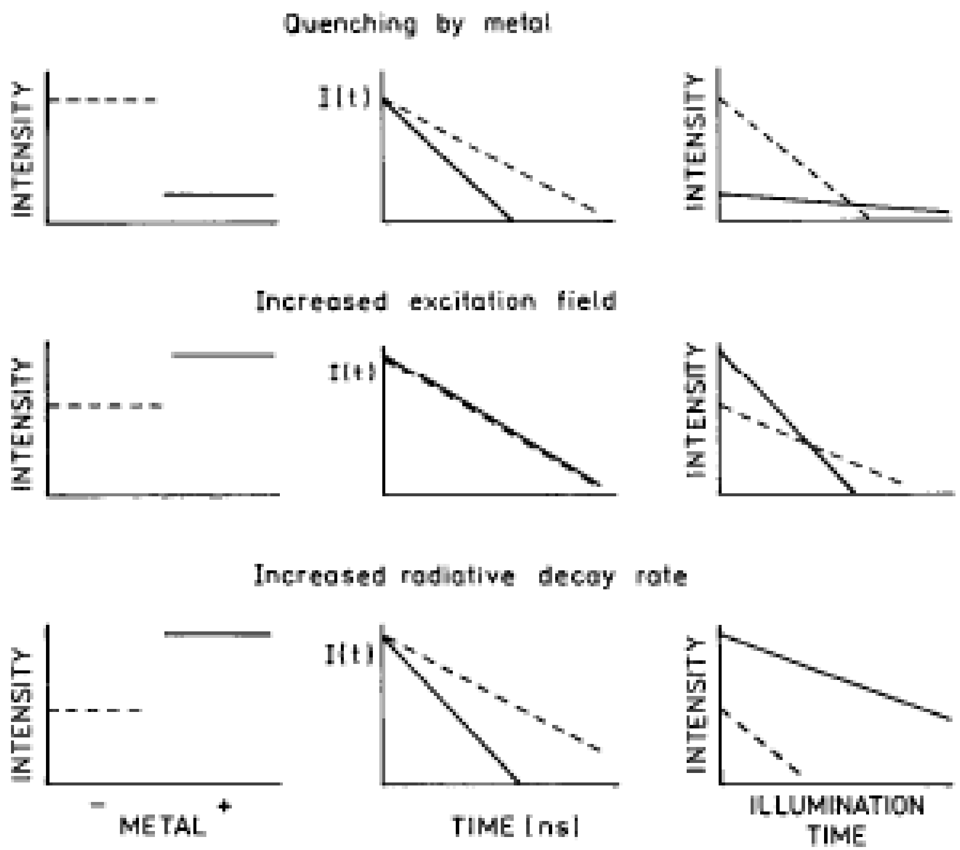
Principle: energy transfer to/from fluorescent molecules



$$\sigma_{abs} = \frac{3\lambda^2}{4\pi}\eta(\gamma, \gamma_r, E_o)$$

$$Q = \frac{\gamma_r}{\gamma_r + \gamma_{nr}}$$





J. Lakowicz, *Ana. Biochem.*,**298**, 1 (2001)

Quenching:
- Decreased intensity
- Decreased life time
- Increased photostability
- Lower # of photons

Enhancement:
- Increased intensity from larger E
- Unaffected life time
- Equal # of photons

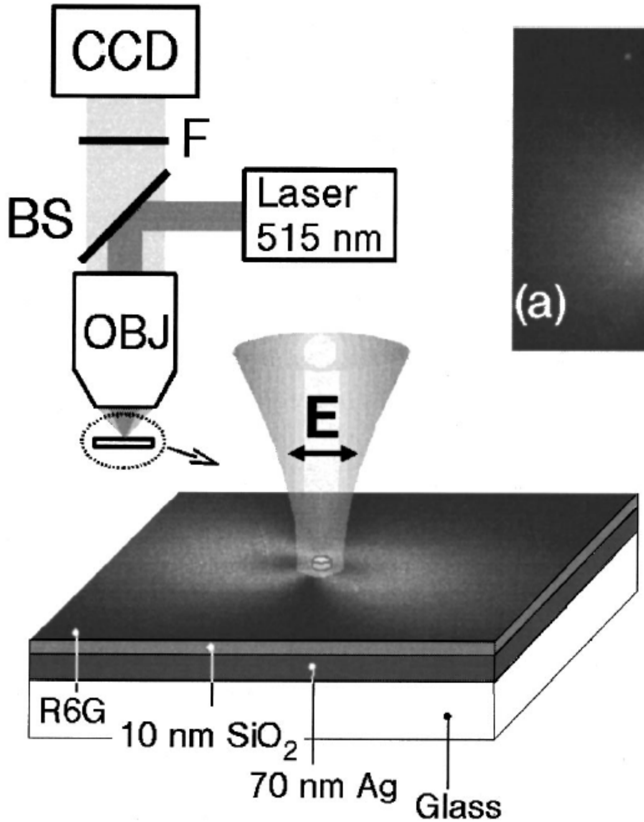
Radiative life-time:
- Increased intensity from higher Q
- Decreased life-time
- Increased photostability
- Higher # photons

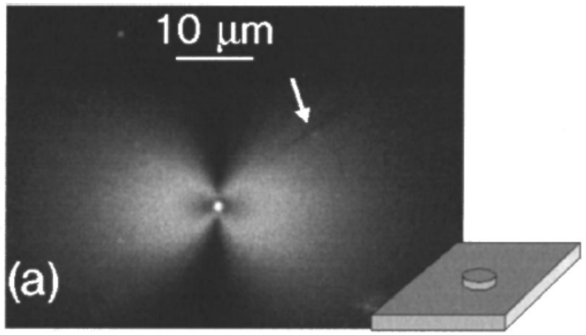
Fluorescence intensity distribution: mapping the SPP

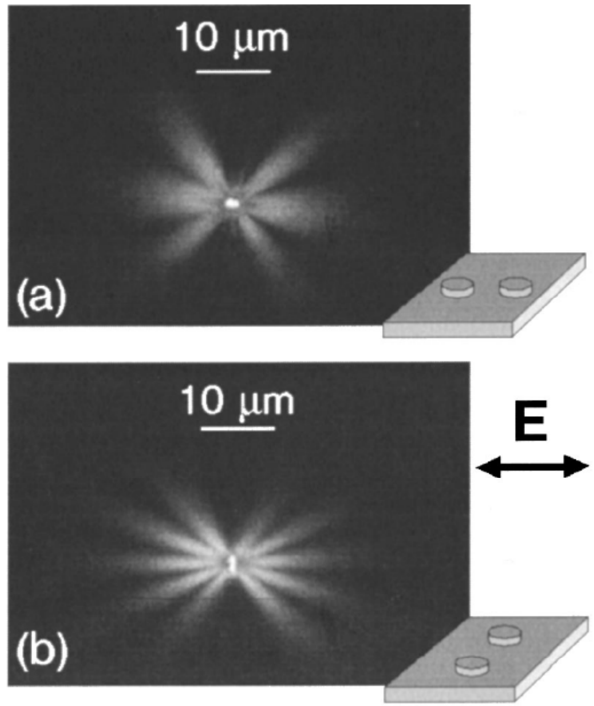
APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 3 21 JANUARY 2002

Fluorescence imaging of surface plasmon fields

H. Ditlbacher, J. R. Krenn, N. Felidj, B. Lamprecht, G. Schider, M. Salerno, A. Leitner, and F. R. Aussenegg
Institute for Experimental Physics and Erwin Schrödinger Institute for Nanoscale Research, Karl-Franzens-University Graz, A-8010 Graz, Austria

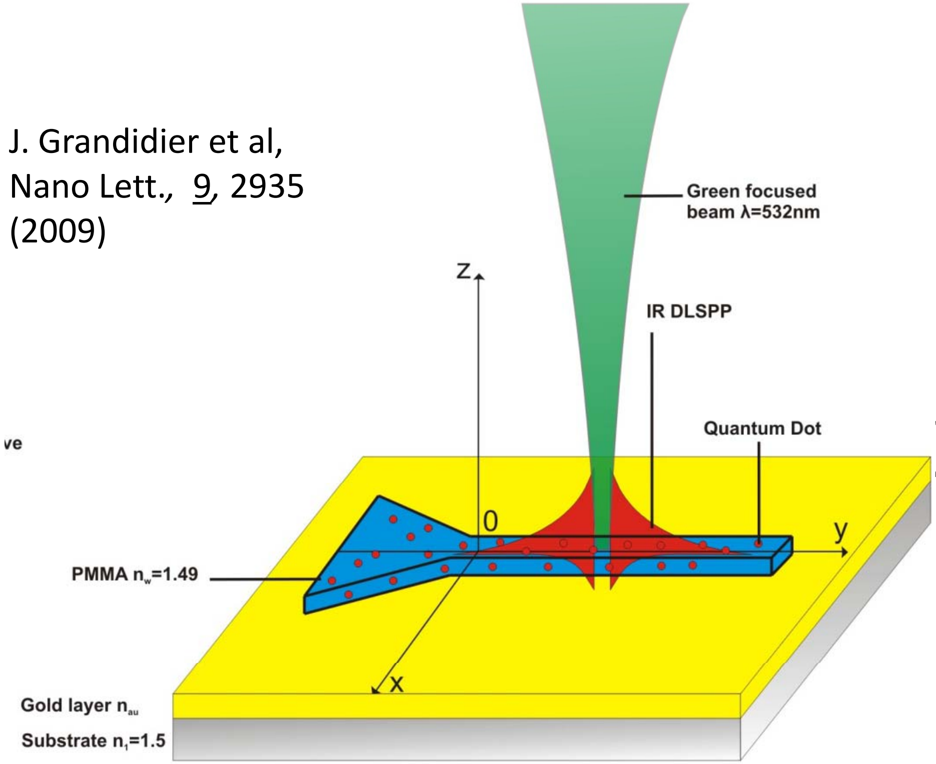




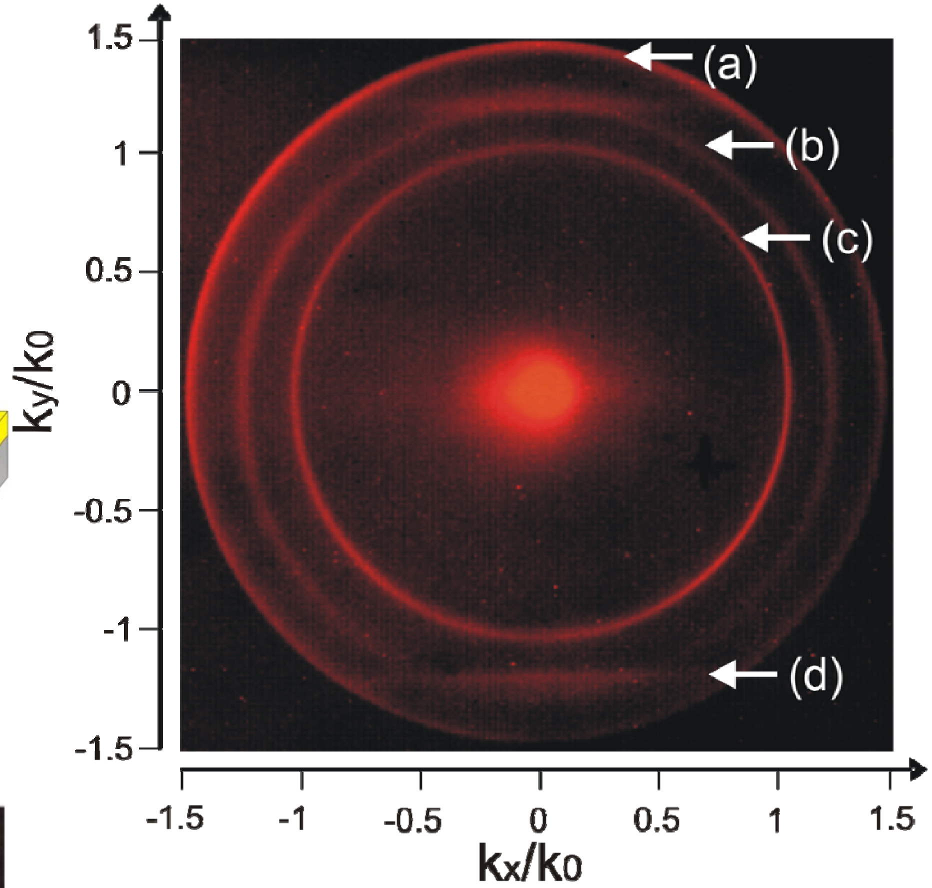


Revealing mode properties through QDs fluorescence

J. Grandidier et al,
Nano Lett., 9, 2935
(2009)



TM$_{00}$ guided mode excited through excitation of QDs
Measured Lspp=9.21µm±0.82µm



(a) Au/Air spp
(b) Au/PMMA TE$_0$ mode
(c) TM$_{00}$ guided mode
(d) Au/PMMA TM$_0$ mode

Pro et contras of Fluorescence Microscopy

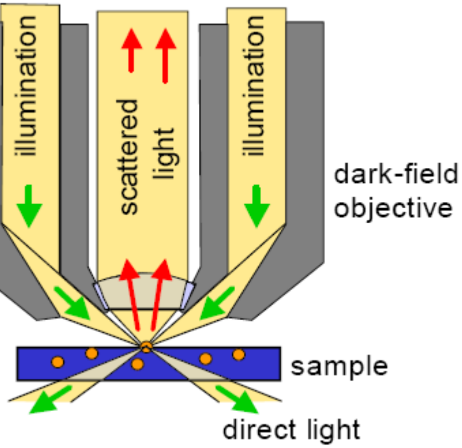
- Local probe
- Large choice of chromophores or QDs (SPP matching wavelength)
- Straightforward excitation and detection
- Access to direct and reciprocal space

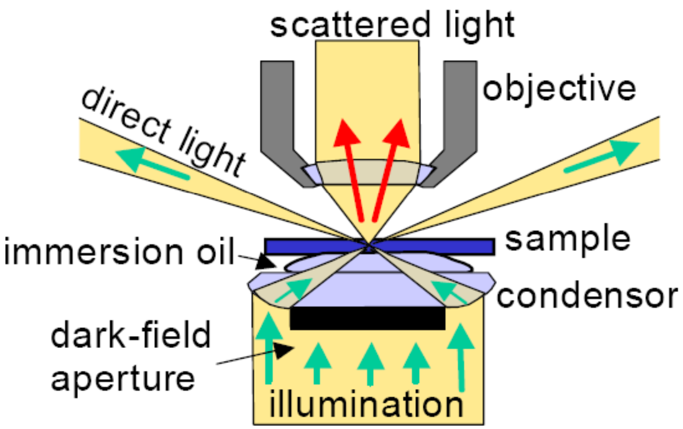
- Limited spatial resolution (diffraction)
- Molecular photobleaching
- Critical to distance from film
- Qualitative information

DARK-FIELD MICROSCOPY

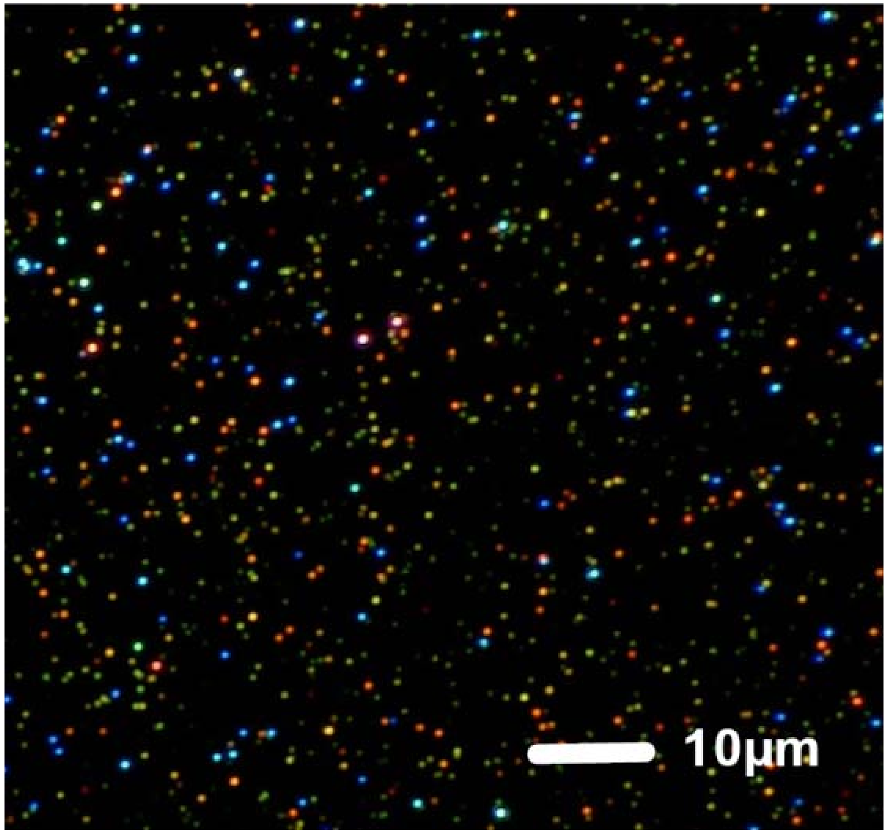
(Colored plasmons)

Principle: rejecting out direct illumination





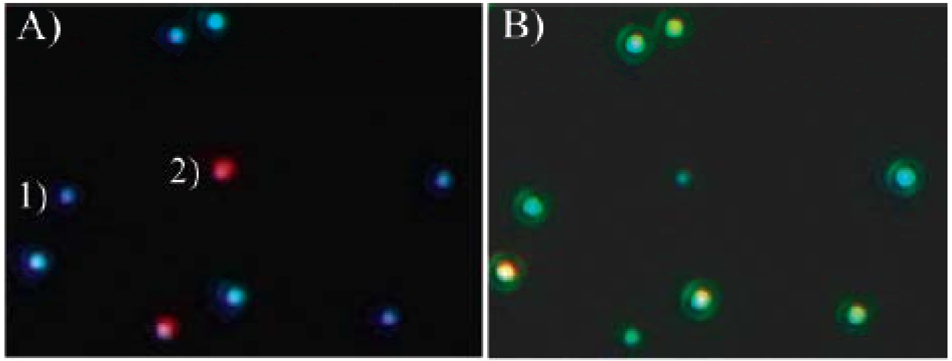
C. Sönnichsen, *Plasmons in metal nanostructures*, PhD thesis, Münich (2001)



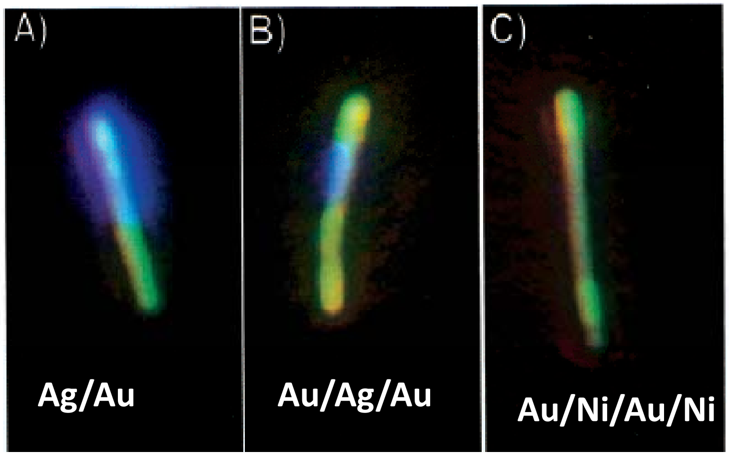
C. Sönnichsen, *Plasmons in metal nanostructures*, PhD thesis, Münich (2001)

Dark-field imaging (and spectroscopy)

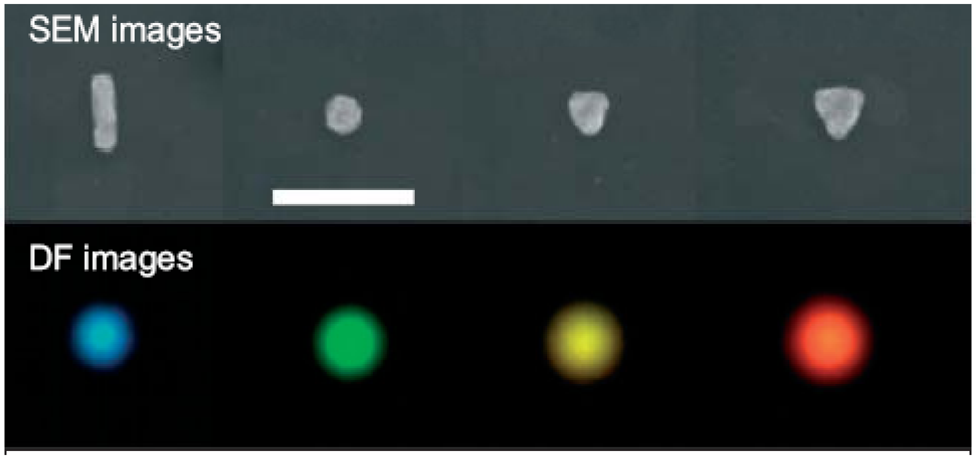
Particles in water Same particles in oil



J. Mock, *Nano Lett.* **3**, 485 (2003)



J. Mock, *Nano Lett.* **2**, 465 (2002)



A. Murray & W. Barnes, *Adv. Mat.* **19**, 3771 (2007)

Pro et contras of dark-field Microscopy

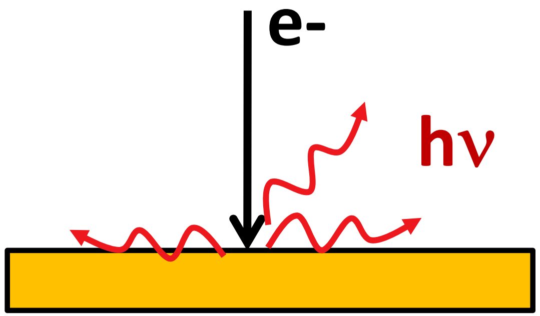
- Complete spectroscopy
- Array and single particle (multiscale) investigations
- Liquid environment

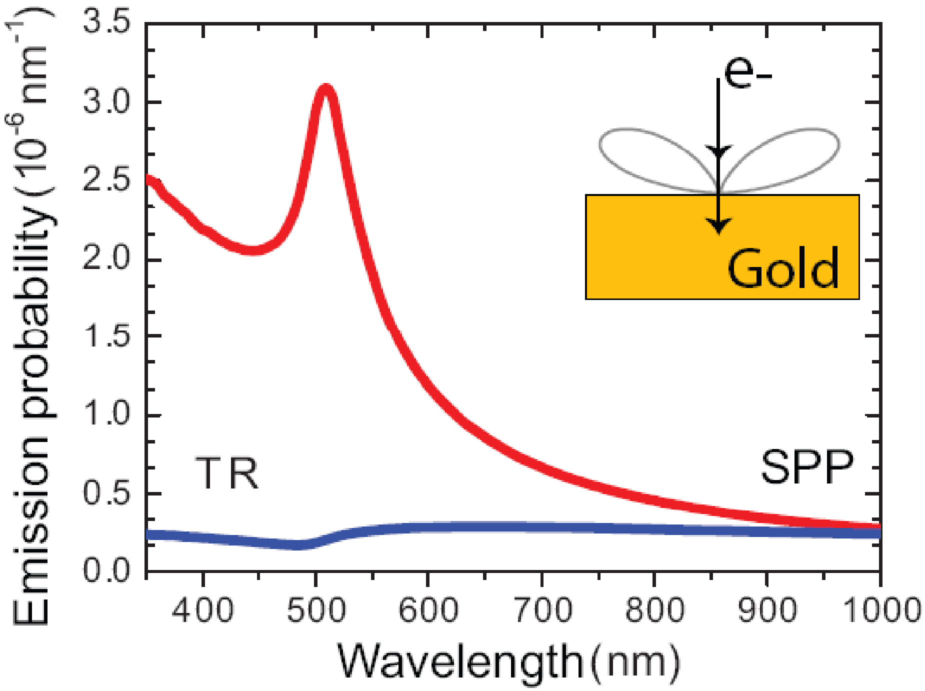
- Limited spatial resolution (diffraction)
- Adapted for localized particle plasmons
- Large particle (>50nm)
- Non-unequivocal

CATHODOLUMINESCENCE MICROSCOPY

(a valse between an e^-, a plasmon, and a photon)

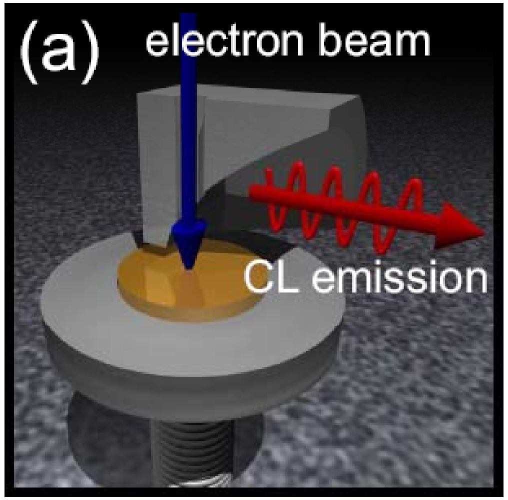
Principle: transition radiation and surface plasmon





Contribution from transition radiation (e- incident on interface) and surface plasmons. Both are coherent with the external field of the electron: interference signal

M. Kuttge, *Cathodoluminescence Plasmon microcsopy*, PhD thesis, Utrecht (2009)



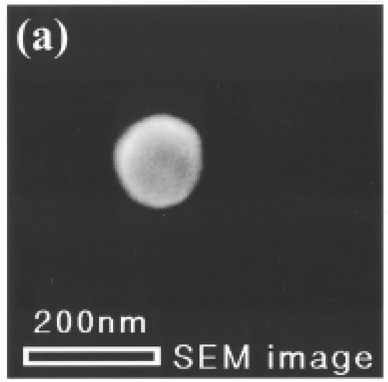
Photon maps and spectroscopy of localized SPP modes

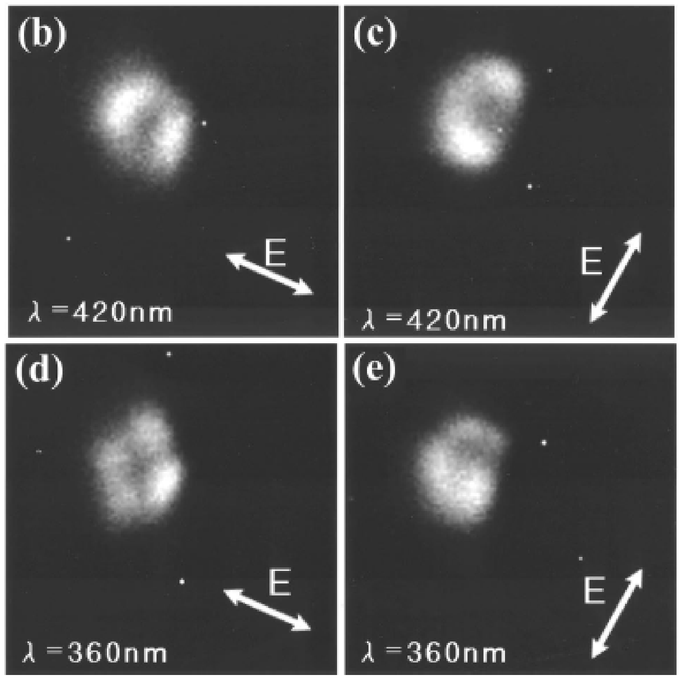
PHYSICAL REVIEW B, VOLUME 64, 205419

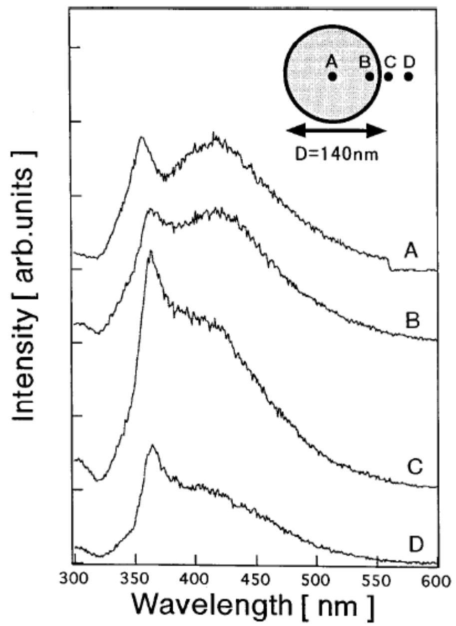
Photon emission from silver particles induced by a high-energy electron beam

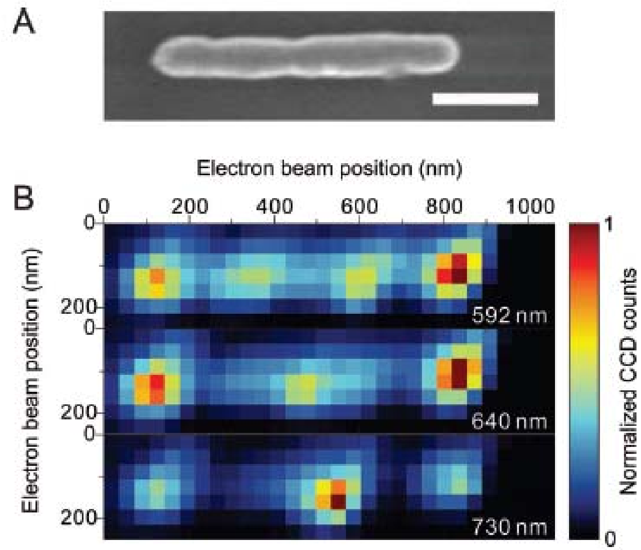
N. Yamamoto and K. Araya
Department of Physics, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan

F. J. García de Abajo
Centro Mixto CSIC-UPV/EHU and Donostia International Physics Center (DIPC), San Sebastián, Spain
(Received 11 July 2000; published 6 November 2001)





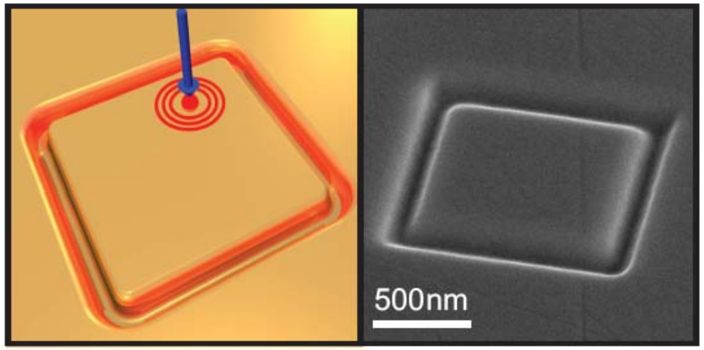


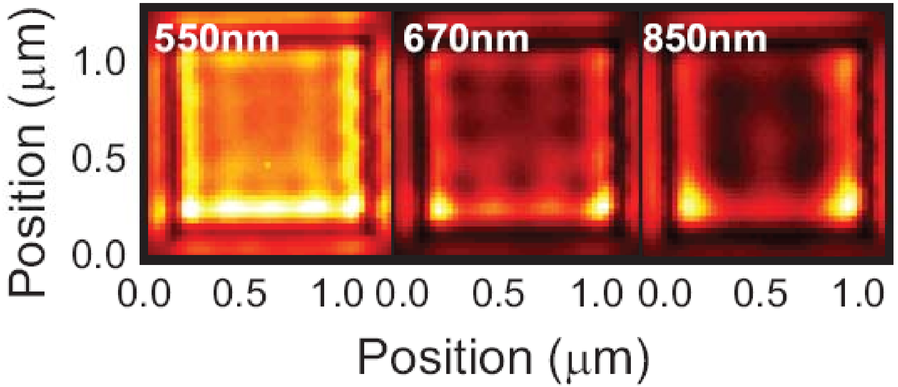


E. Vesseur et al., *Nano. Lett.* 7, 2843 (2007)

Photon maps of propagative SPP modes

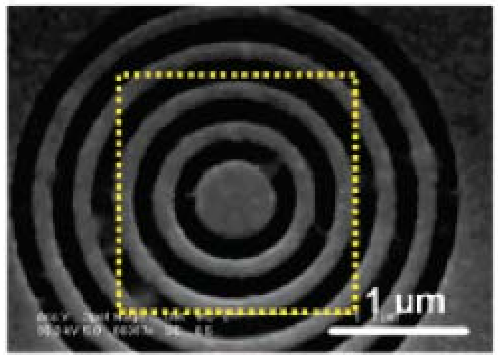
Boxed plasmons

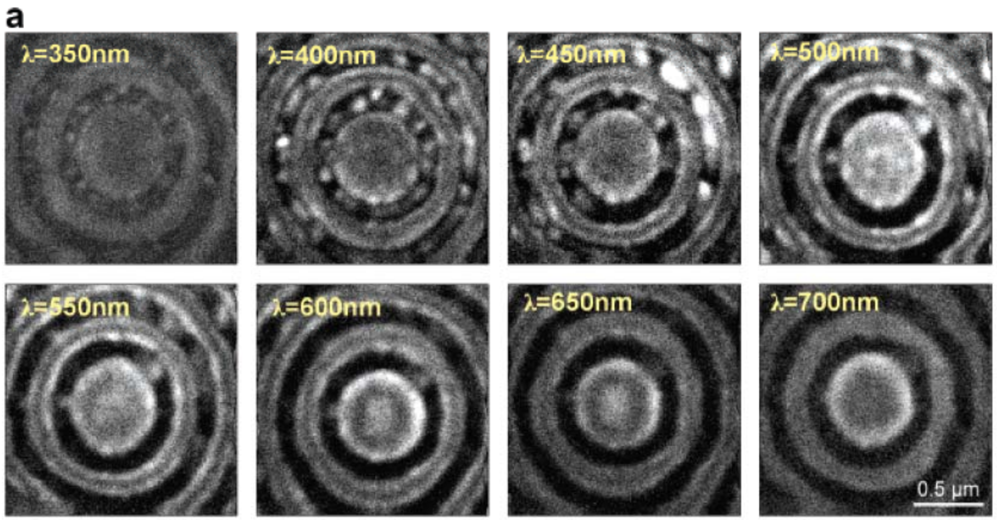




M. Kuttge, *Cathodoluminescence Plasmon microcsopy*, PhD thesis, Utrecht (2009)

Resonators





C. Hofmann et al., *Nano. Lett.* 7, 3612 (2007)

Pro et contras of Cathodoluminescence Microscopy

SPP point source (nm size)
Spatial and spectral investigations
Imaging of localized and propagative SPP modes

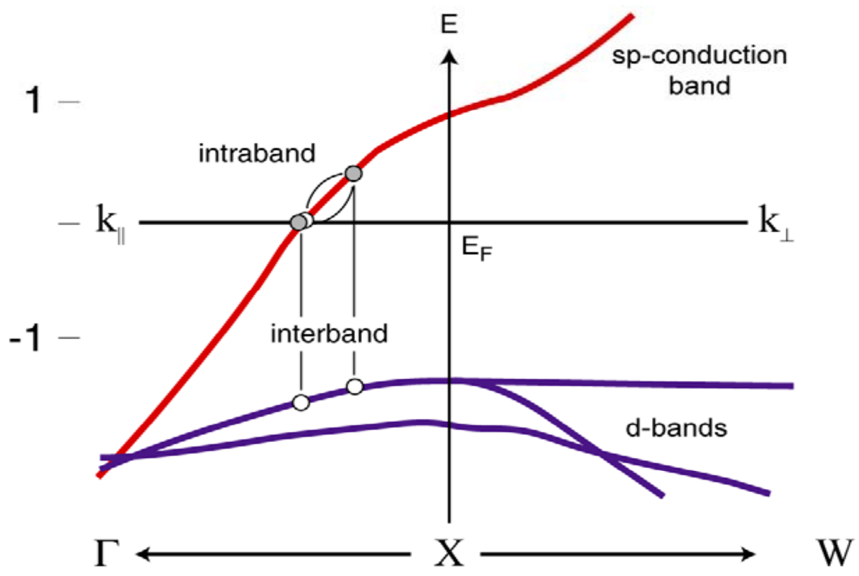
Vacuum environment
Low efficiency (10^{-6}/nm)
Interference contrast

(NON LINEAR) CONFOCAL MICROSCOPY

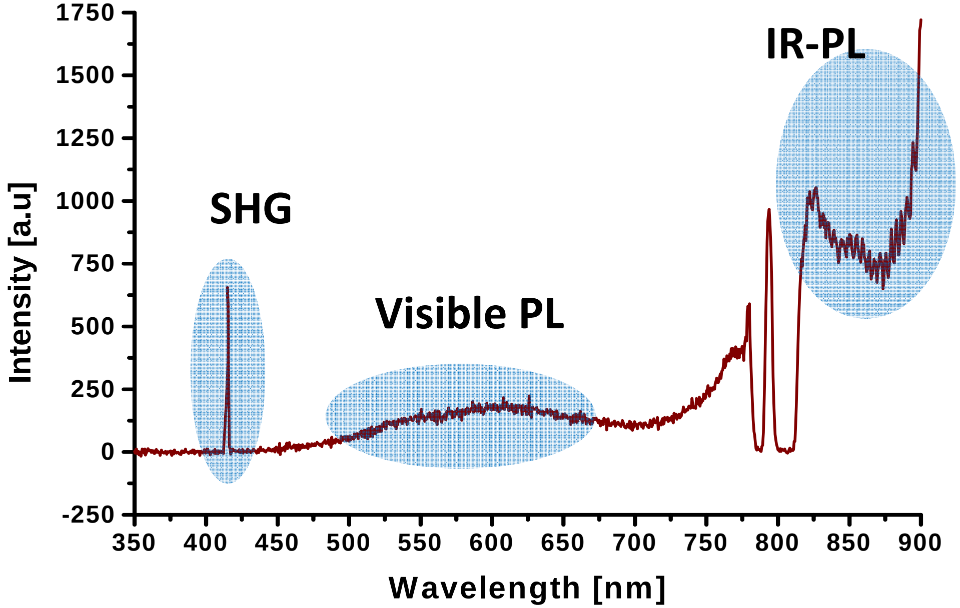
(Blurred plasmons)

Gold: a luminescent material!

- Visible photoluminescence originates from interband electronic transitions from *d*-band electrons to the conduction band
- IR PL originates from intraband transitions
- Second-harmonic is generated by a non-linear surface susceptibility



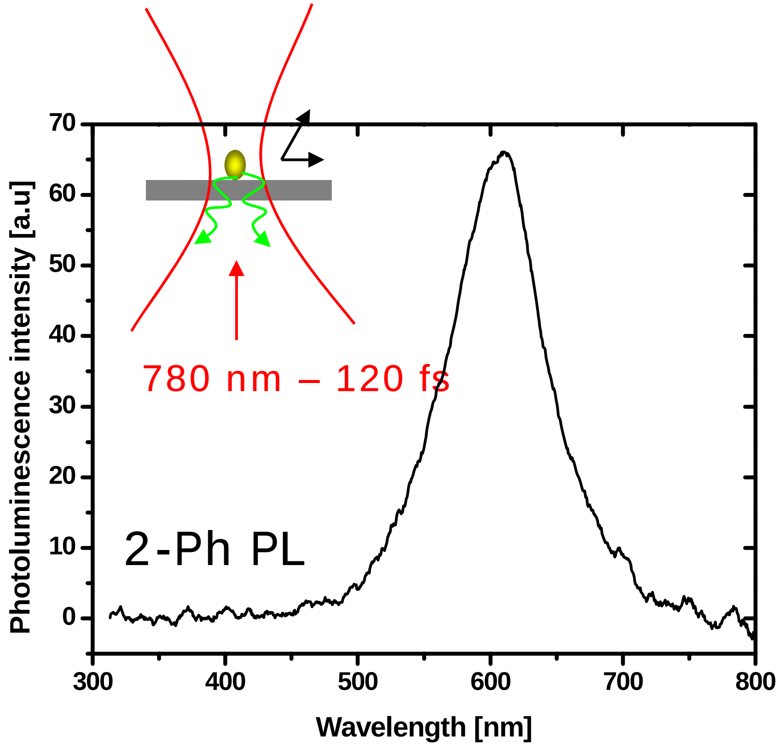
O. Jepsent et al., *Phys. Rev. B.* 23, 2684 (1981).
M. Guerrisi et al, *Phys. Rev. B.* 12, 557 (1975).

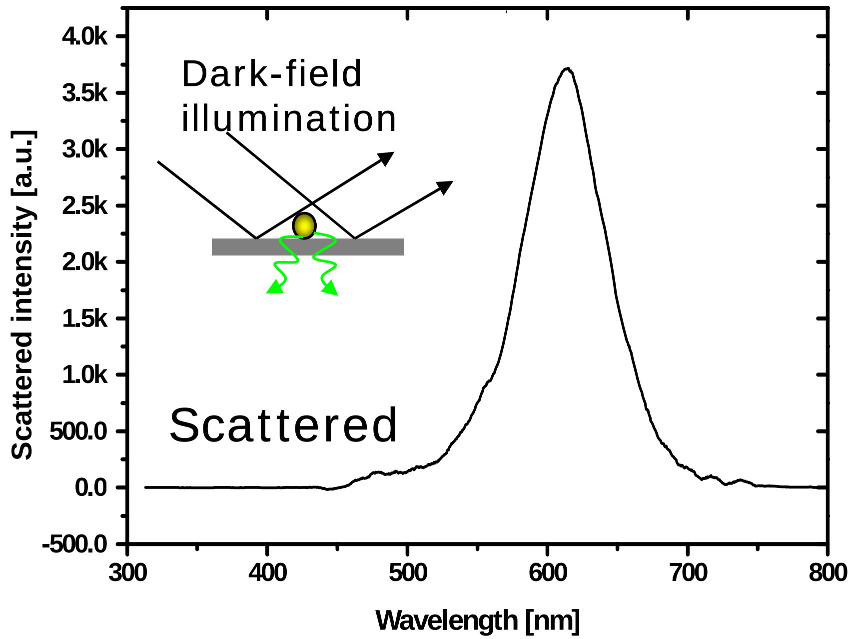


M. Beversluis, A. Bouhelier, and L. Novotny, *Phys. Rev. B*, 68, 115433 (2003)

Gold PL and plasmons

- The PL emission is modulated by the surface plasmon resonance

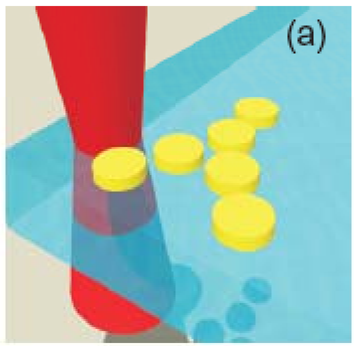


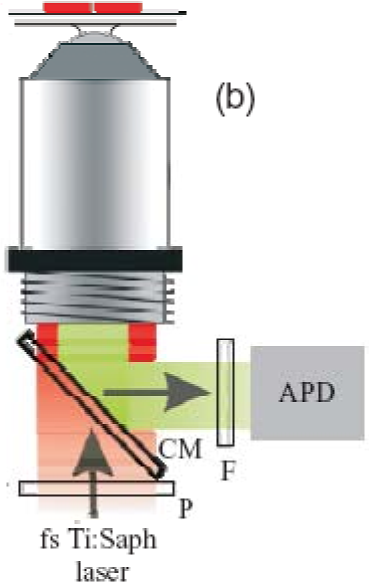


A. Bouhelier, et al. *Phys. Rev. Lett.* 95, 267405 (2005)

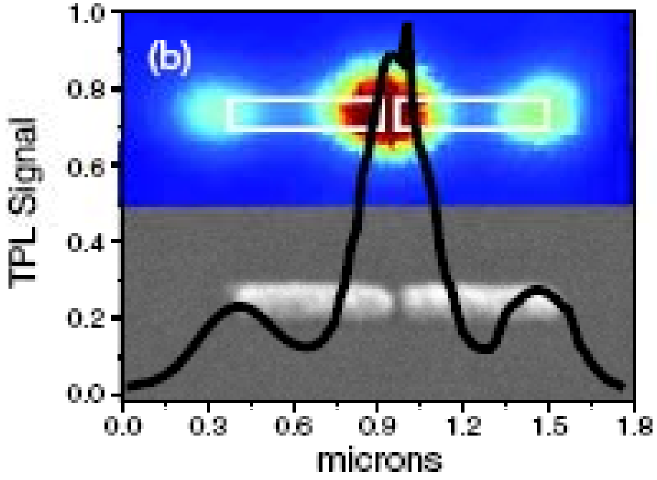
The surface plasmon plays a double role here: create a local field enhancement to increase the number of PL photons and also provide a fast radiative e^- relaxation process through SP emission

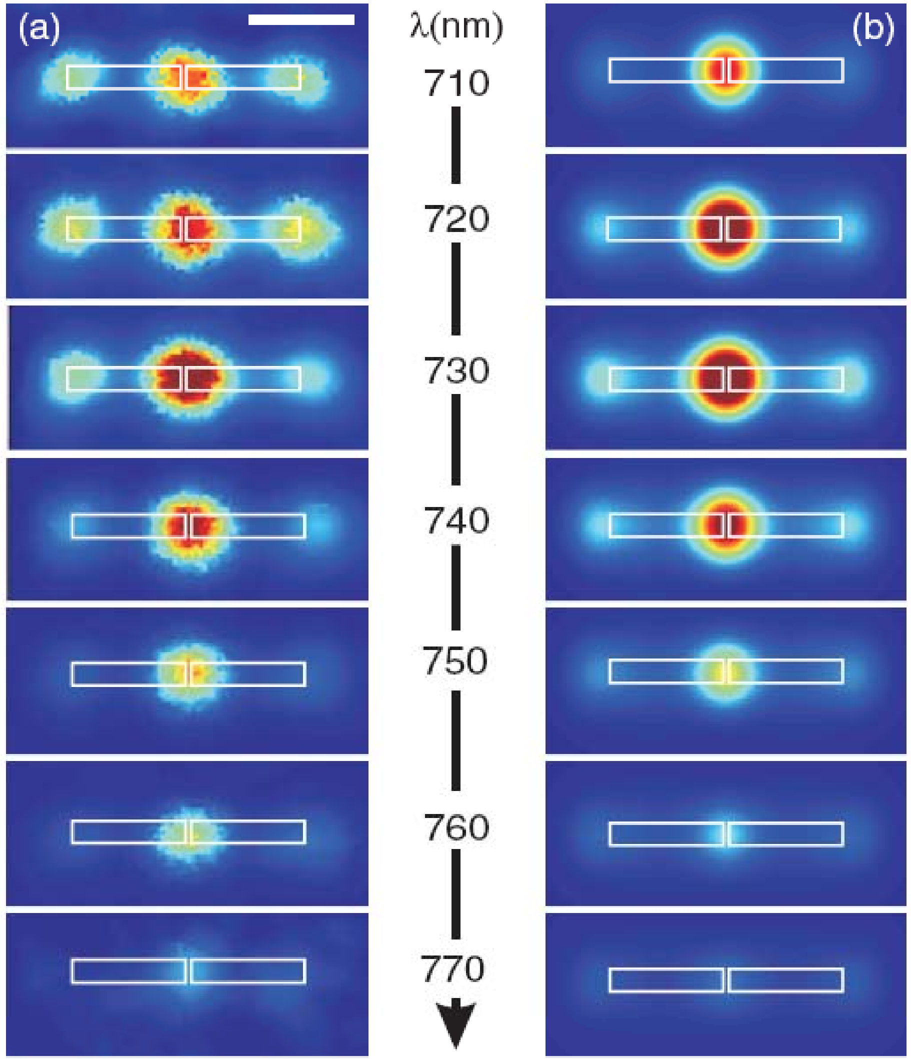
Imaging PL spatial distribution





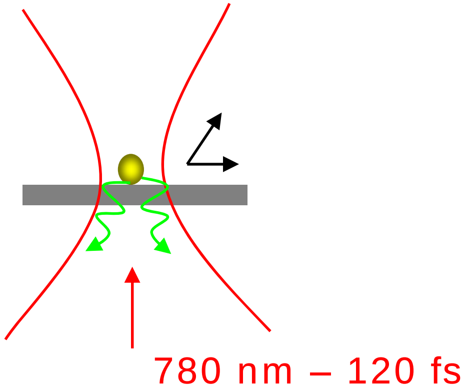
P. Ghenuche, et al. *New J. Phys.* 10, 105013 (2008)

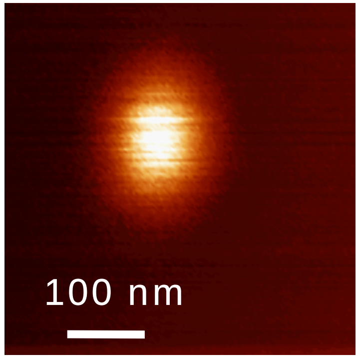




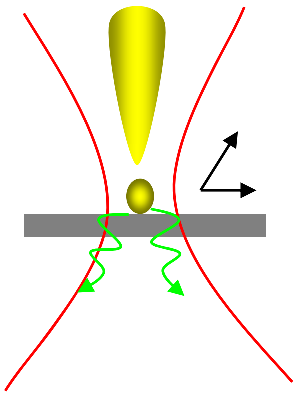
P. Ghenuche, et al. *Phys. Rev. Lett.* 101, 116805 (2008)

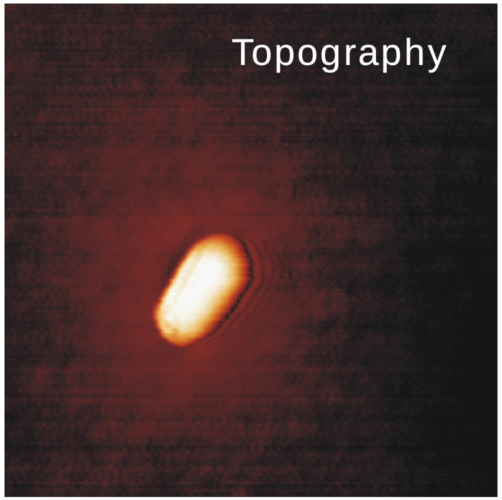
Parenthesis: near-field non-linear imaging

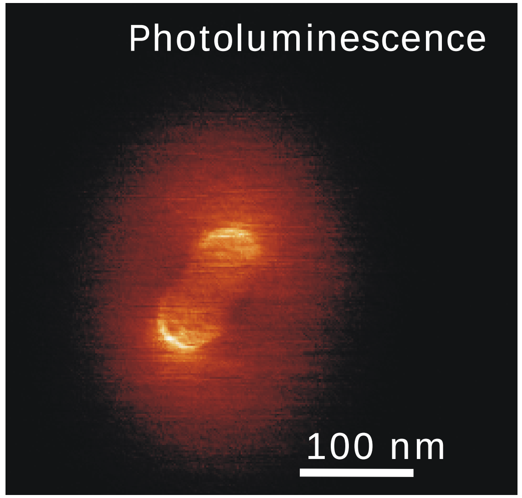




Confocal far field







A. Bouhelier, M. Beversluis, and L. Novotny, *App. Phys. Lett.* 83, 5041 (2003)
K. Imura, T. Nagahara, and H. Okamoto, *J. Am. Chem. Soc.* **126**, 12730 (2004)

Pro et contras of confocal Microscopy

Diffraction-limited resolution

Indirect measurement

Ultrafast laser system

Not perturbative (for “low” peak power)

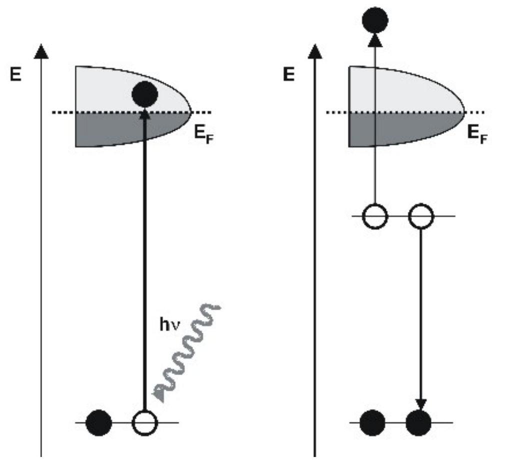
Sensitive to field magnitude (non linear)

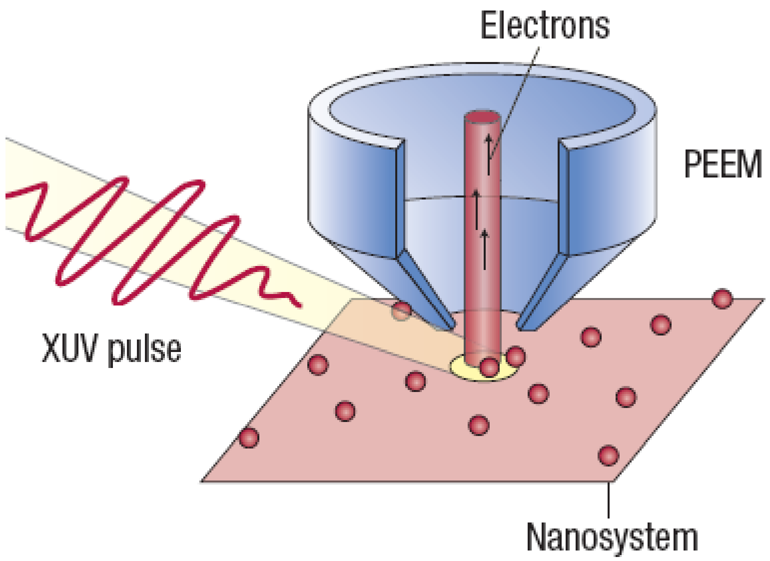
Spectroscopy (with caution)

PHOTOELECTRON EMISSION MICROSCOPY

(a valse between photon(s), plasmons, and e^-)

Photo-electron emission





1) Upon photo-excitation (Xray, UV), electrons are excited above Fermi level, creating holes on core levels
2) Auger scattering leads to electron emission above the work function
3) Broad distribution of energy between the excitation energy and the work function

Role of the plasmon: electron yield proportional to E^4

M. Nisoli, Nat. Photo. _1_, 499 (2007)

Ultrafast dynamics in space and time

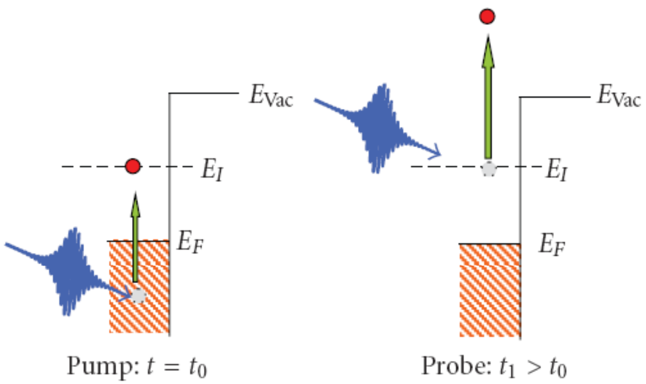
Femtosecond Imaging of Surface Plasmon Dynamics in a Nanostructured Silver Film

NANO LETTERS
2005
Vol. 5, No. 6
1123−1127

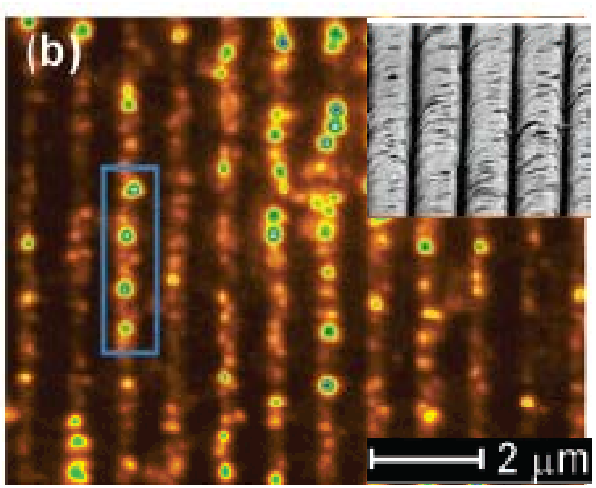
Atsushi Kubo,[†,§] Ken Onda,[†,§] Hrvoje Petek,[*,†,§] Zhijun Sun,[‡,§] Yun S. Jung,[‡,§] and Hong Koo Kim[‡,§]

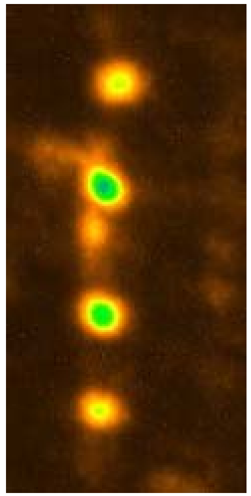
Department of Physics and Astronomy, Department of Electrical Engineering, and Institute of NanoScience and Engineering, University of Pittsburgh, Pittsburgh, Pennsylvania 15260

Interferometric time-resolved two-photon photoemission (ITR-2PP) and photoelectron emission microscopy (PEEM).

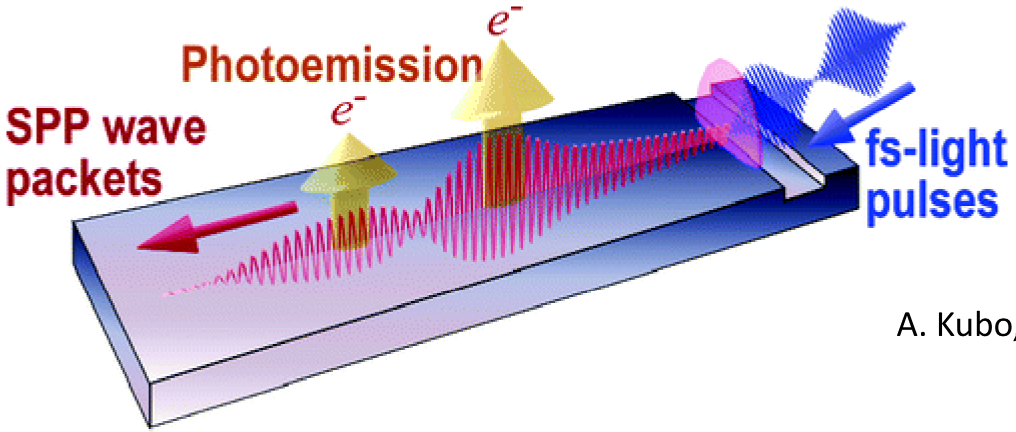


D. Bayer, et al. *J. Nano. Mat. 249514* (2008)

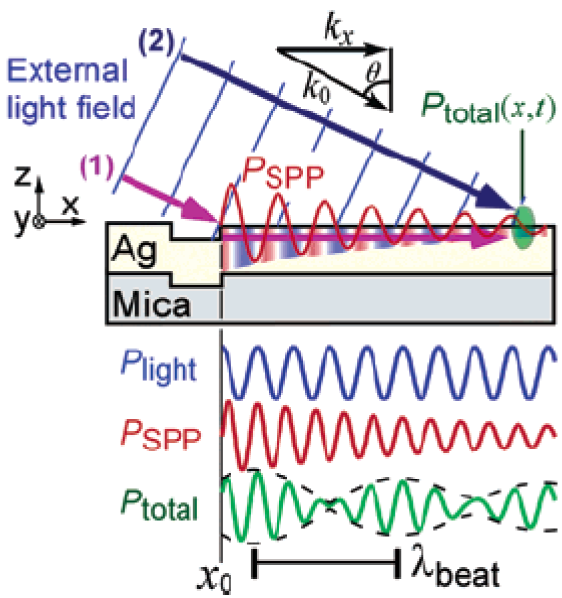


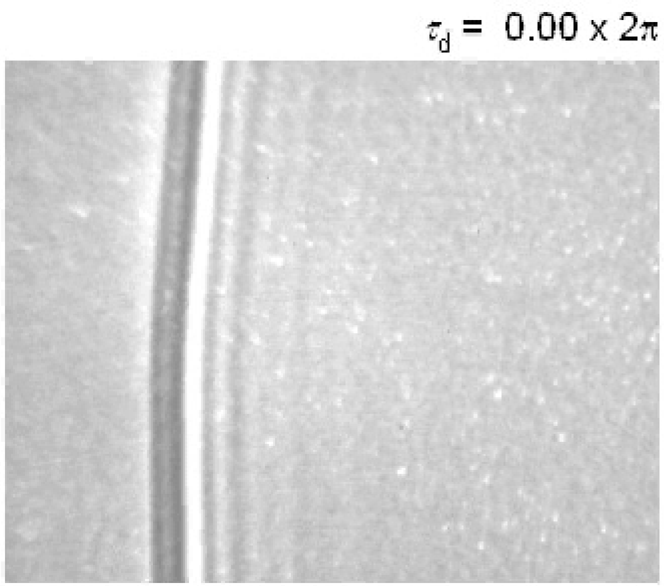


Ultrafast dynamics in space and time



A. Kubo, et al. *Nano Lett. 7, 470* (2007)





Resolving mode structures

Short Range Plasmon Resonators Probed by Photoemission Electron Microscopy

NANO LETTERS
2008
Vol. 8, No. 3
935-940

Ludovic Douillard,* Fabrice Charra, and Zbigniew Korczak†

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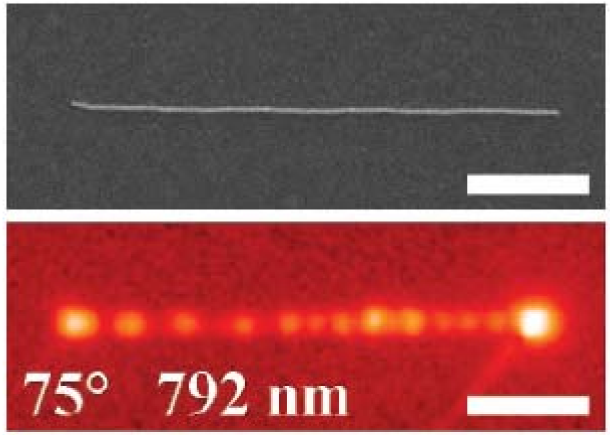
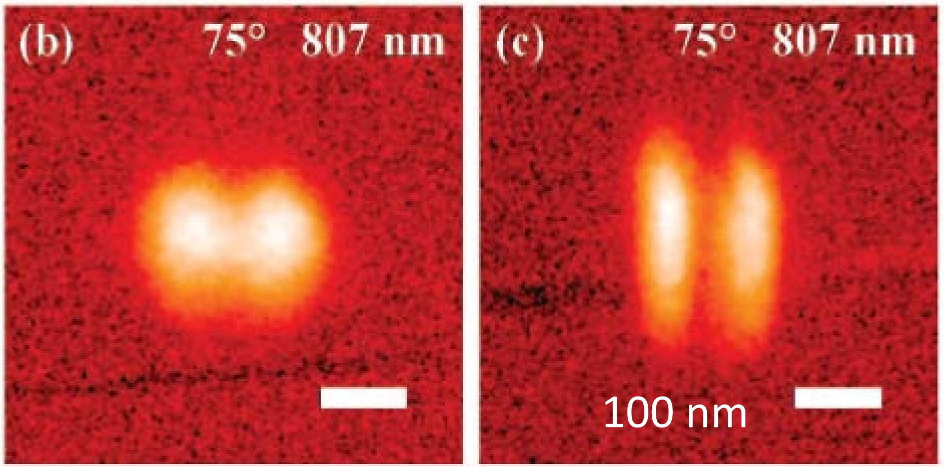
Renaud Bachelot, Sergei Kostcheev, Gilles Lerondel, Pierre-Michel Adam, and Pascal Royer

Laboratoire de Nanotechnologie et d'Instrumentation Optique, ICD CNRS FRE 2848, Université de Technologie de Troyes, 12 rue Marie-Curie, BP 2060,

F-10010 Troyes, France





Dipolar mode in short nanorods

Pro et contras of PEEM

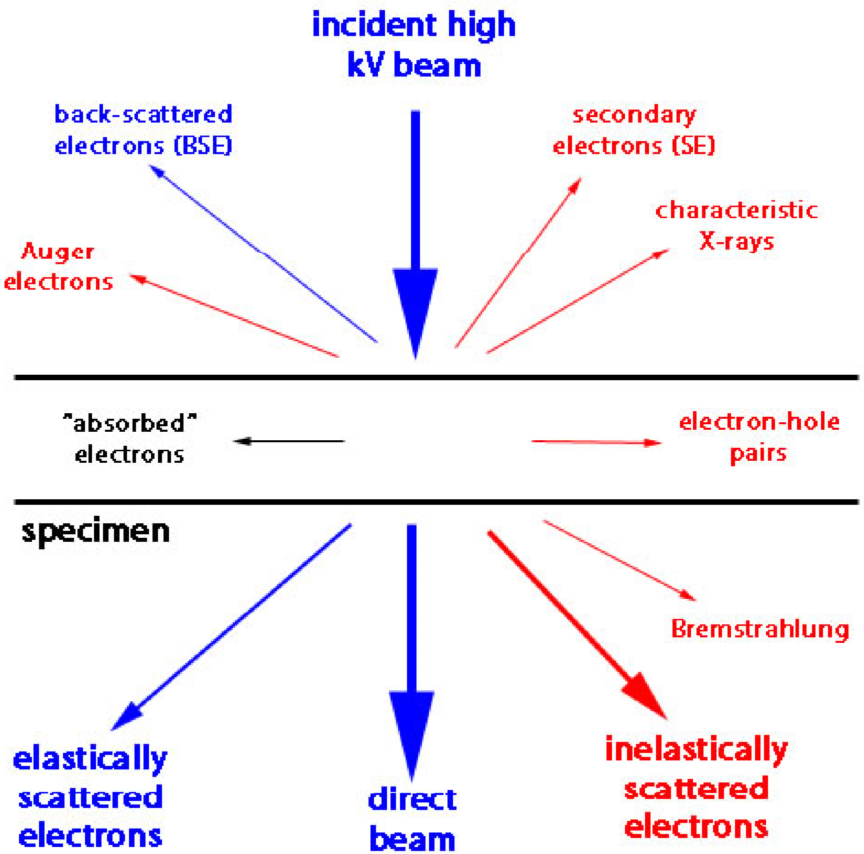
- Nanometer scale resolution (~25 nm)
- Sub-fs time resolution
- Energy resolution (TOF-PEEM)
- Coherent control of SPP field

- UHV environment
- Chromatic aberrations
- Limited to short-wavelength resonance (multi-photon process, electron yield to E^4)

ELECTRON-ENERGY LOSS IMAGING

(a nanoscale detective)

Principle of operation



modified from Williams & Carter (1996) Fig. 1.3

- Raster scanning the electron beam across the sample
- EELS spectrum @ each pixel
- fix energy, plot the amplitude of the spectra for each pixel to reconstruct 2D-image

The sampling volume (beam size) is smaller than the spatial variation of the field

EELS Mapping

Mapping surface plasmons on a single metallic nanoparticle

nature physics | VOL 3 | MAY 2007 | www.nature.com/naturephysics

JAYSEN NELAYAH[1], MATHIEU KOCIAK[1], ODILE STÉPHAN[1]*, F. JAVIER GARCÍA DE ABAJO[2], MARCEL TENCÉ[1], LUC HENRARD[3], DARIO TAVERNA[1], ISABEL PASTORIZA-SANTOS[4], LUIS M. LIZ-MARZÁN[4] AND CHRISTIAN COLLIEX[1]

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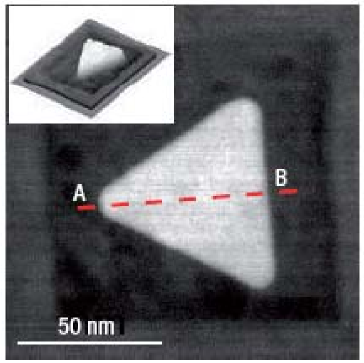
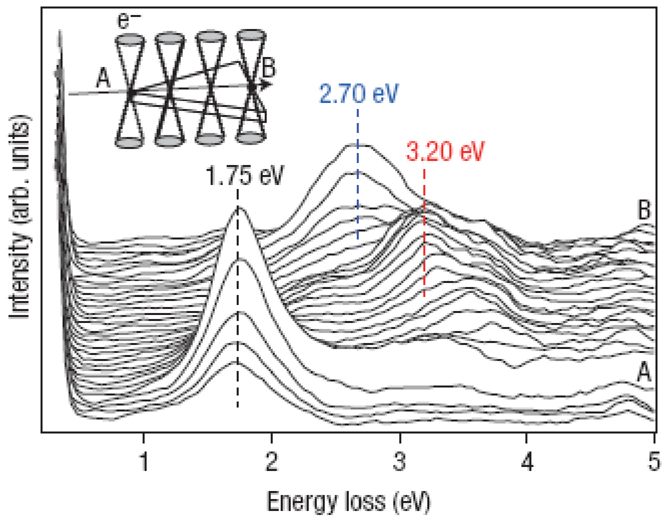
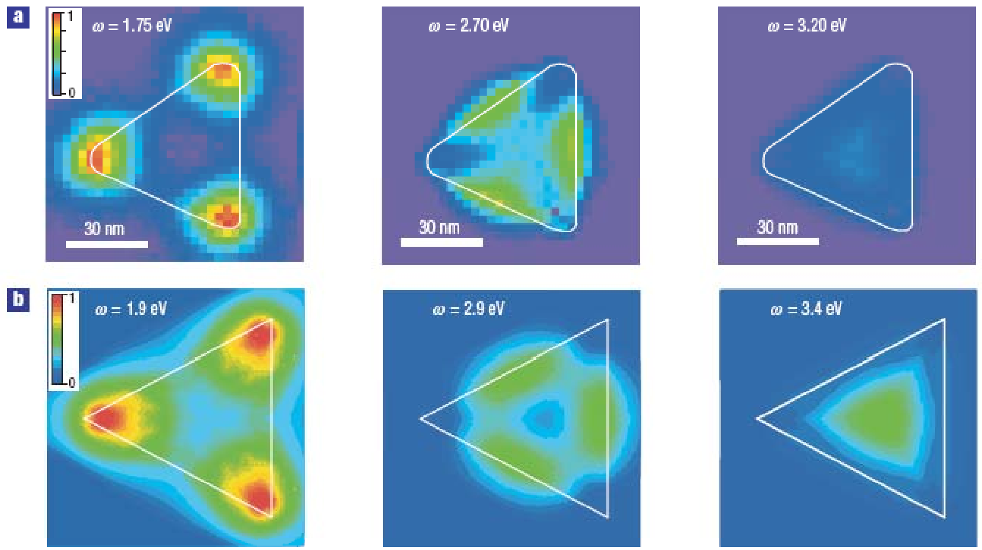
[4]Departamento de Química Física, Universidade de Vigo, 36310 Vigo, Spain
*e-mail: stephan@lps.u-psud.fr







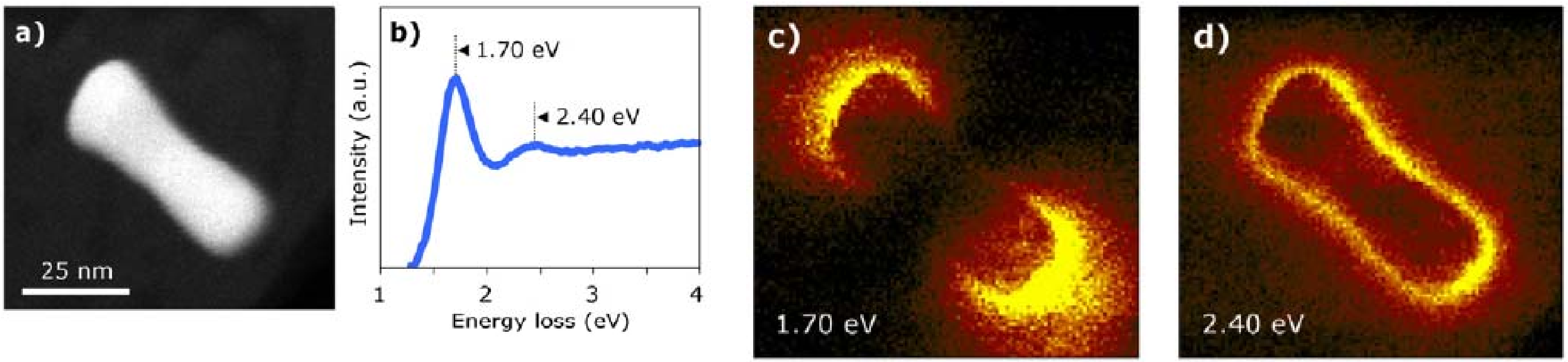
EELS Mapping

IOP Publishing NANOTECHNOLOGY

Nanotechnology **18** (2007) 165505 (5pp) doi:10.1088/0957-4484/18/16/165505

Mapping surface plasmons at the nanometre scale with an electron beam

Michel Bosman[1], Vicki J Keast[2], Masashi Watanabe[3], Abbas I Maaroof[4] and Michael B Cortie[4]



Pro et contras of EELS mapping

+

- Unprecedented resolution (< 5nm)
- Relationship between shape, localization & energy
- Investigation to high energies (bulk plasmon)
- Direct measurement of energy exchange (access to the dielectric function of the material)

−

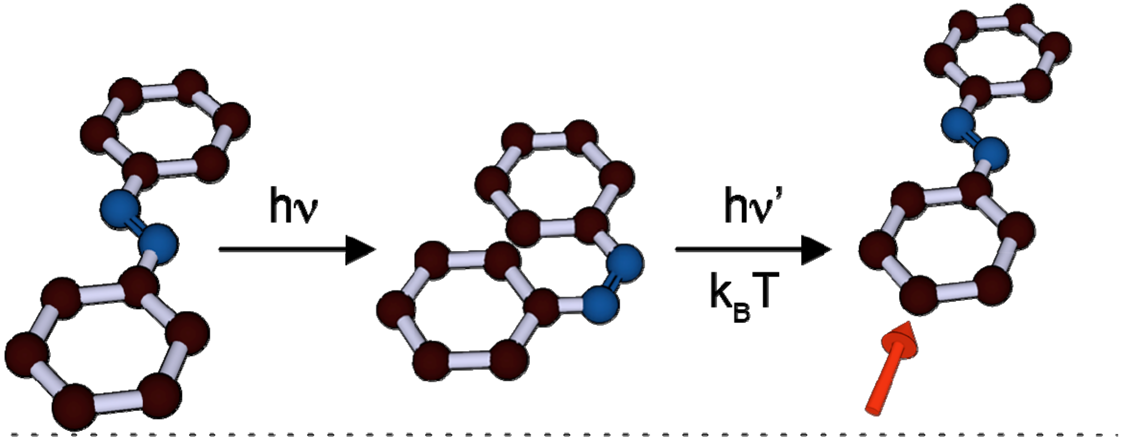
- UHV environment
- Deconvolution for plasmon bands close to the zero-loss peak

PHOTOCHEMICAL IMAGING

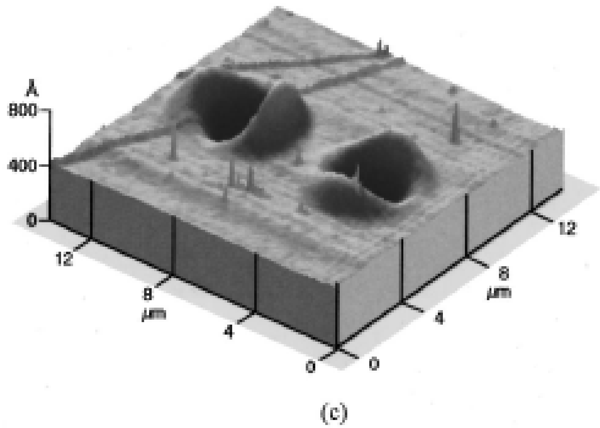
(through topography)

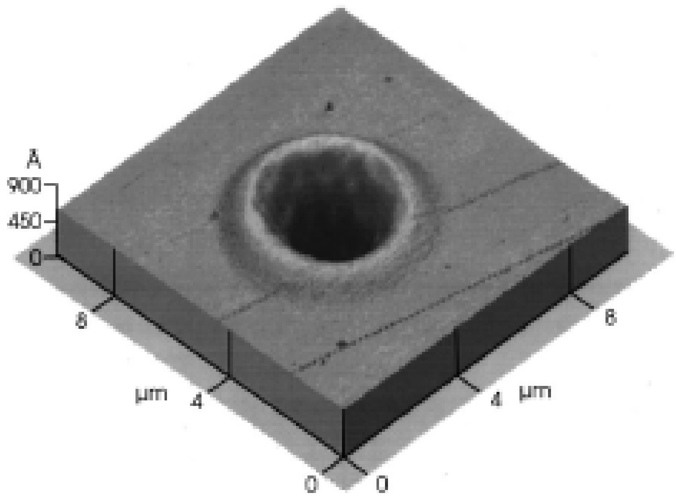
Principle of operation: isomerization and diffusion

- Repetitive *Trans-Cys-Trans* cycles introduce translational molecular diffusion



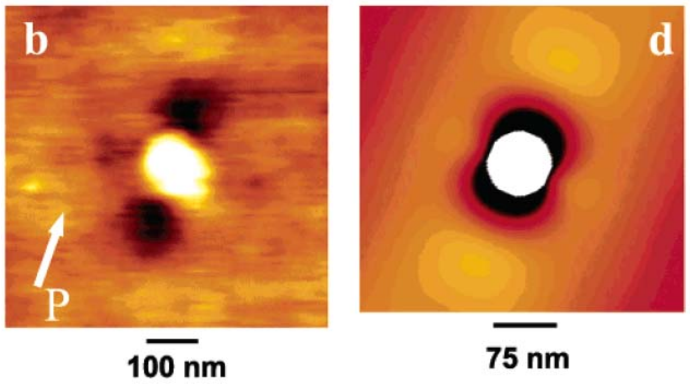
Courtesy of Prof. Plain, UTT Troyes



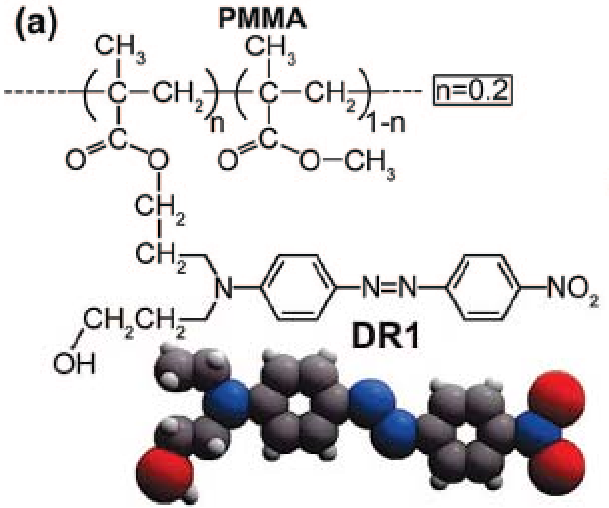


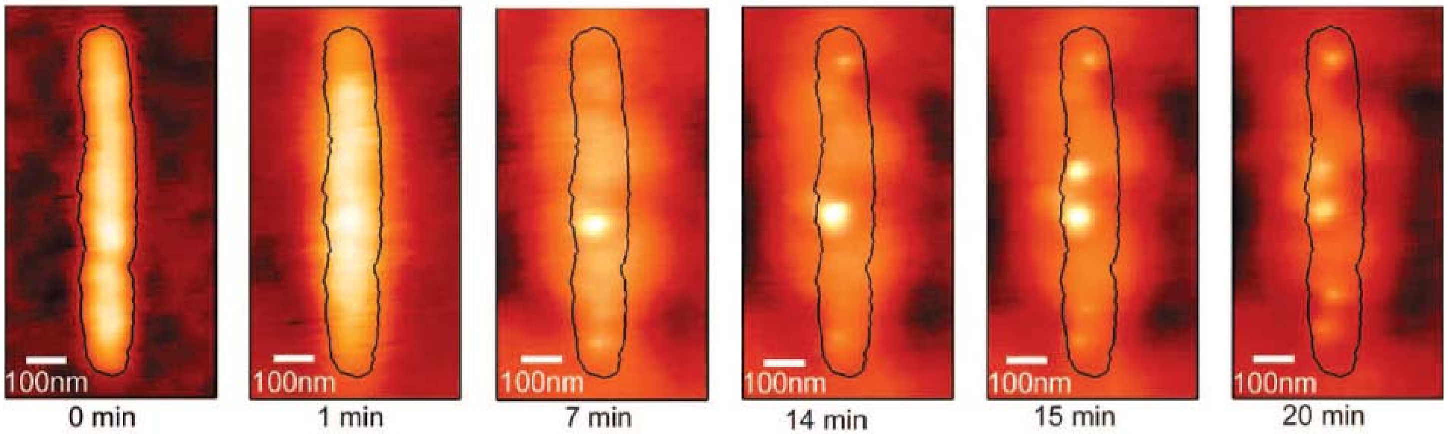
S. Bian, et al. *J. Appl. Phys.* 86, 4498 (1999)

Photochemical imaging of localized SPs



C. Hubert, et al. *Nano Lett.* 5, 615 (2005)





M. Juan, et al. *J. Phys. Chem. A* 113, 4647 (2009)

Pro et contras of photochemical imaging

+

- Vectorial approach (field sensitivity)
- Control over molecular mass transport
- In principle, molecular resolution

-

- Limited wavelength range
- Dependence to temperature
- Second-order measurement
- Relatively complex modeling required for interpretation

Conclusion

Reflectivity

- Interface sensitivity
- Dispersion
- Indirect access to Lspp
- Application to « sensoring »

Spectroscopy

- Influence of shape, materia, polarization, environment...
- Enhancement
- Life-time

EELS

- Electronic surface excitations(transitions)
- Dispersion
- Cristallinity

Imaging

- Spatial distribution
- Controlled enhancement
- Guiding and processing
- Plasmonic circuitry

POST-DOC(S)
AND
PHD(S) WANTED!!

Bio-plasmonics, integrated plasmonics
& molecular plasmonics

Contact: alexandre.bouhelier@u-bourgogne.fr