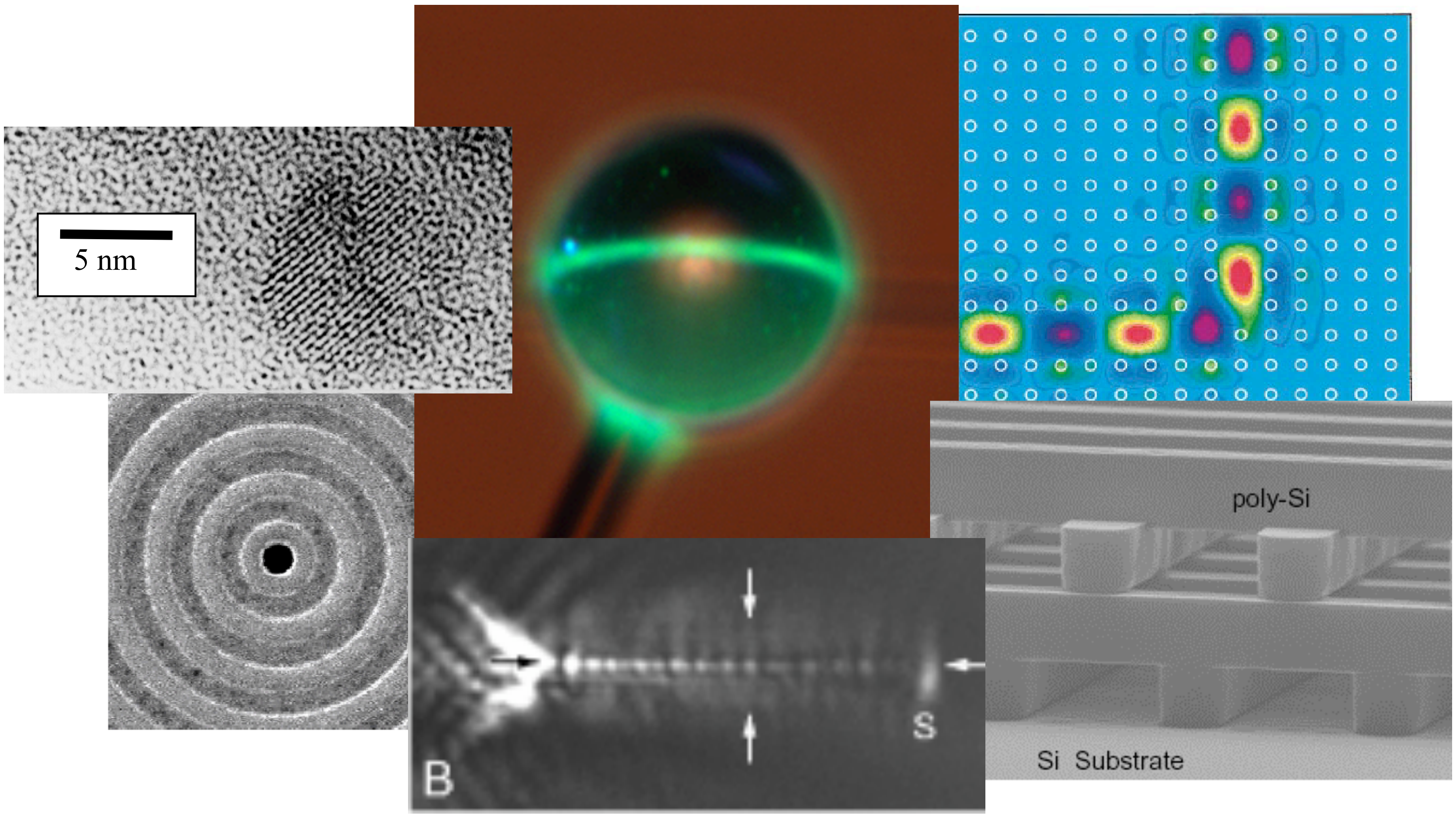
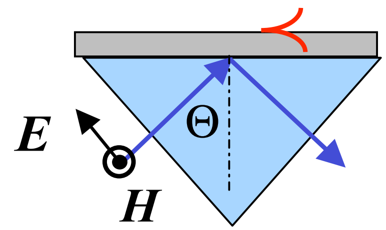
Lecture 11: Guiding Light Along Nanoparticle Arrays



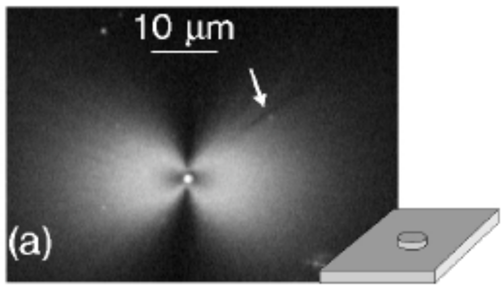
What happened at the last Lecture

Coupling light to surface plasmon-polaritons

- Kretchman geometry $$k_{//,SiO_2} = \sqrt{\varepsilon_d}\,\frac{\omega}{c}\sin\theta = k_{sp}$$



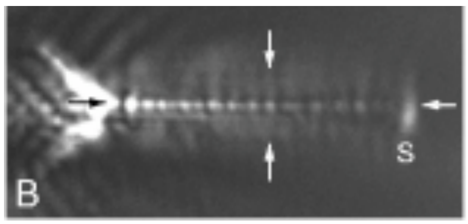
- Grating coupling $$\boldsymbol{k}_{//,Air} = \boldsymbol{k}_{sp} \pm m\boldsymbol{G}$$



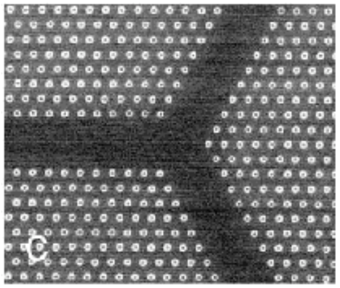
- Coupling from a metal dot

Guiding geometries

- Stripes and wires



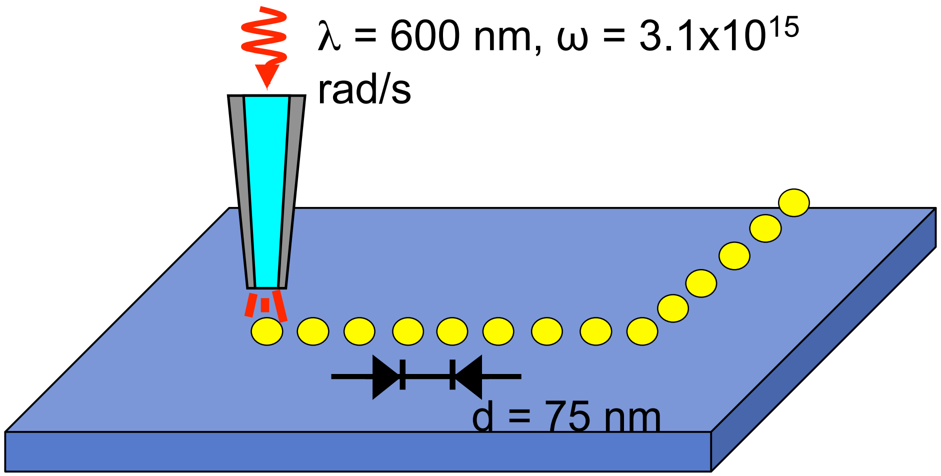
- Line defects in hexagonal arrays (2d photonic crystals)



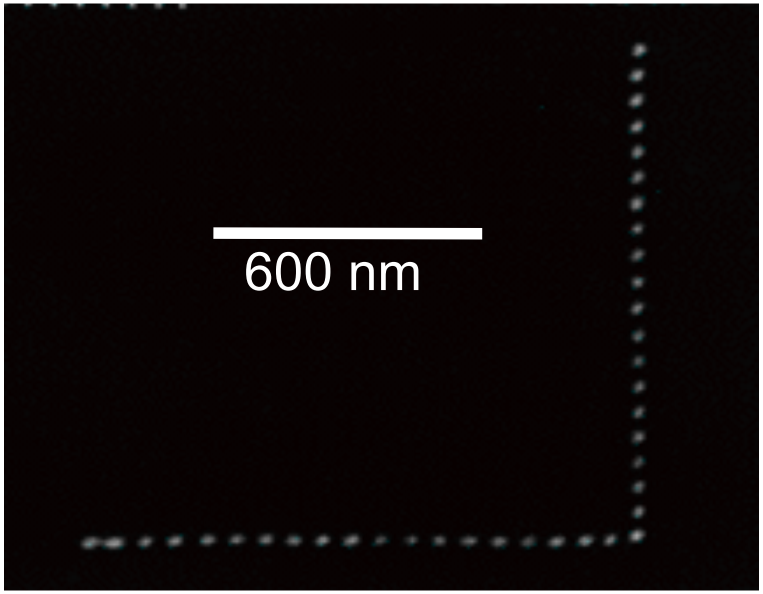
- Today: nanoparticle arrays

Guiding of light along an array of Au nanoparticles ?

- Near field optical excitation



- SEM of array of 50 nm Au particles

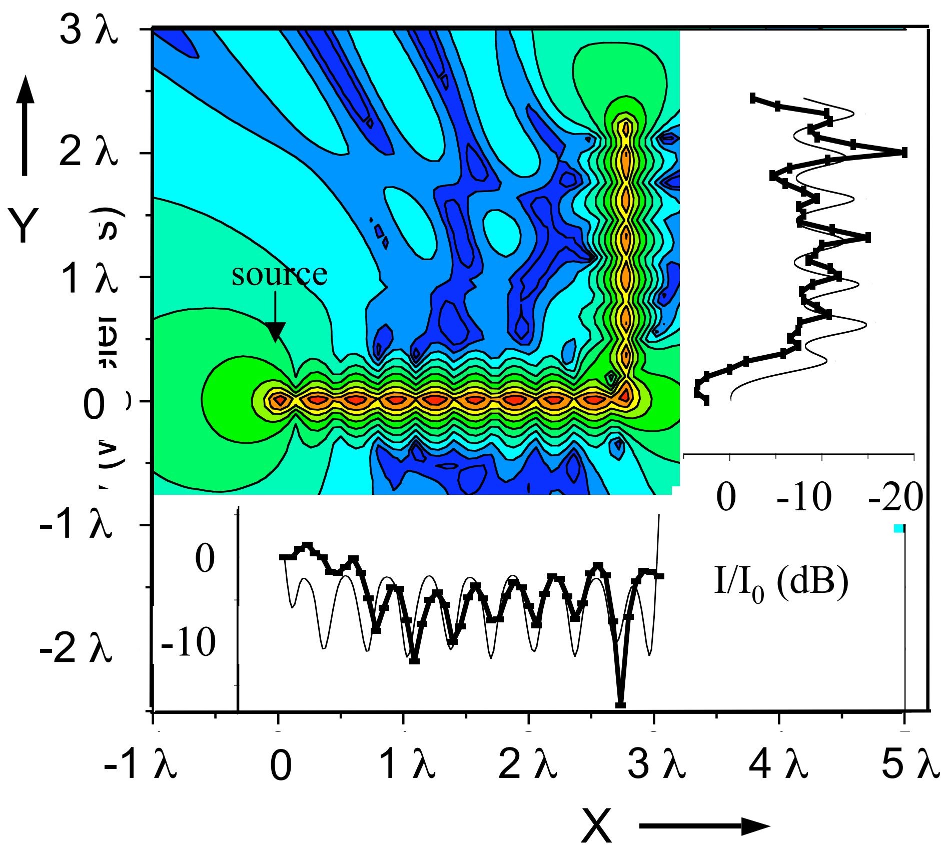


- Light and microwaves are electromagnetic waves described by Maxwell's equations

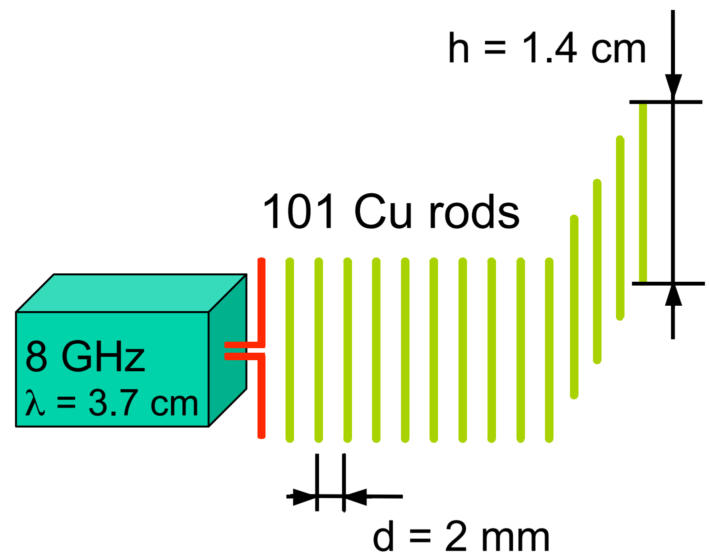
S.A. Maier, M.L. Brongersma H.A. Atwater, Appl. Phys. Lett. 78, 16, 2001

A cm-scale Analogue to a Plasmonic Device

Plot of $|E_z|$ on a logarithmic scale



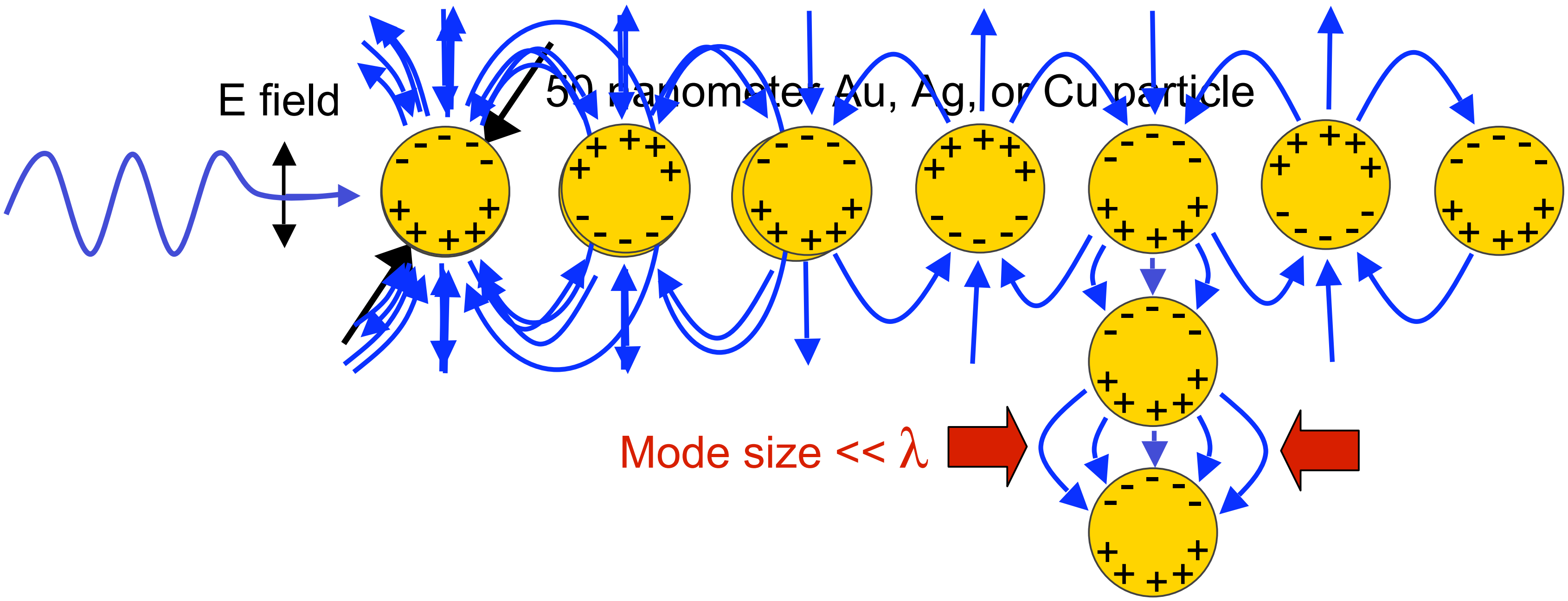
Experimental setup



Stefan A. Maier et al.,
Appl. Phys. Lett. 78, 16, 2001

- 90% of the energy is confined within a distance of $0.05\lambda_F$
- 3-4 dB loss at a corner due far-field radiation

EM Near-field Interaction between Nanoparticles



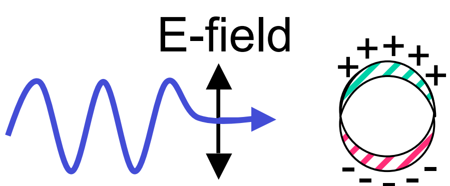
- Light can penetrate metallic nanoparticles and set the electrons in motion
- This collective electron motion is called a plasmon
- Plasmonics: Guiding "light" along metallic nanostructures
- Loss per unit length ≈ 3 dB/μm …. Loss per device may be manageable

Excitation of a Single Metal Nanoparticle

Particle

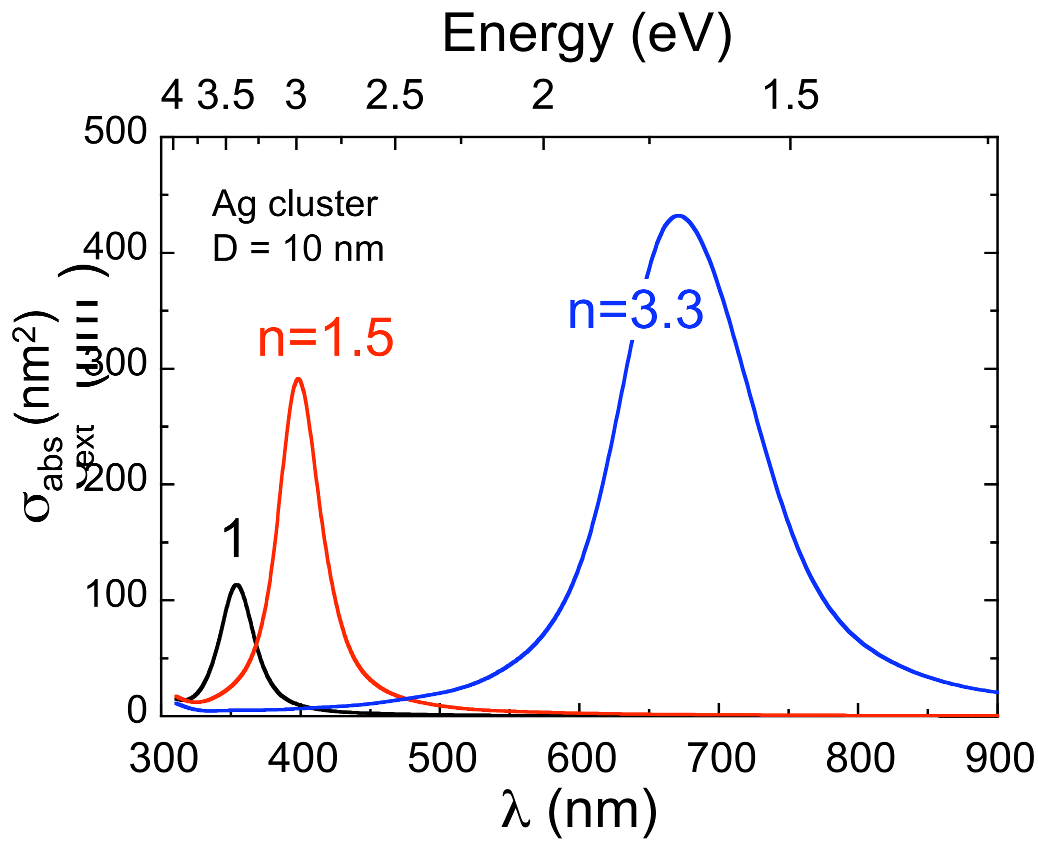
Volume = V_0

$\varepsilon_M = \varepsilon_{1,M} + i\varepsilon_{2,M}$



Host matrix

$\varepsilon_H = \varepsilon_{1,H} =$



$$\sigma_{abs}(\omega) = 9\frac{\omega}{c}\varepsilon_H^{3/2}V_0 \frac{\varepsilon_{1,M}(\omega)}{\left[\varepsilon_{1,M}(\omega) + 2\varepsilon_H\right]^2 + \varepsilon_{2,M}(\omega)^2}$$

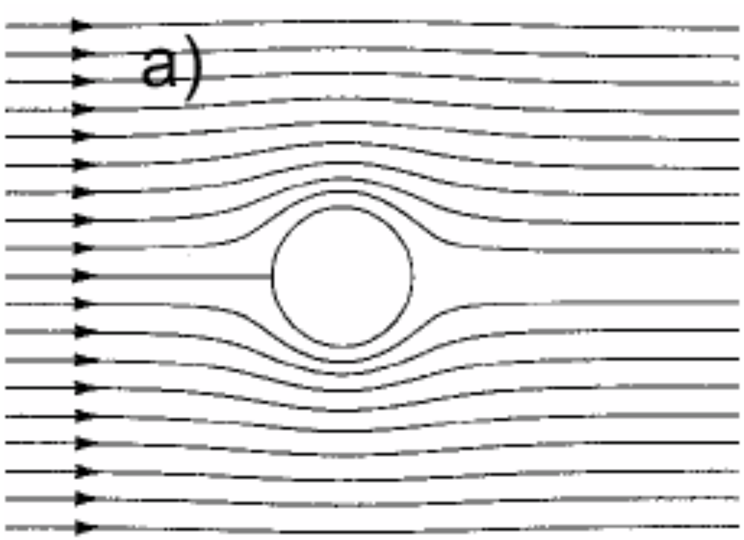
G. Mie Ann. Phys. 25, 377 (1908)

Origin Enhanced Absorption Cross-section

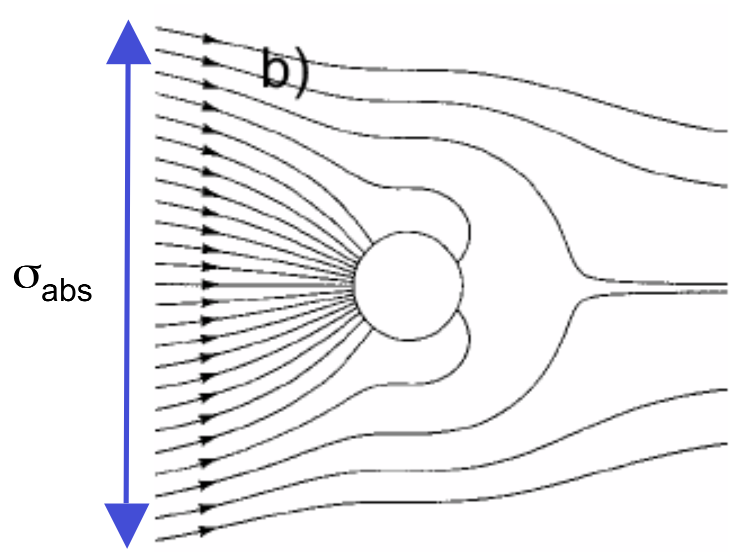
Poynting vector

Energy flux (Poynting vector) for a plane wave incident on a metallic nanoparticle

Off resonance

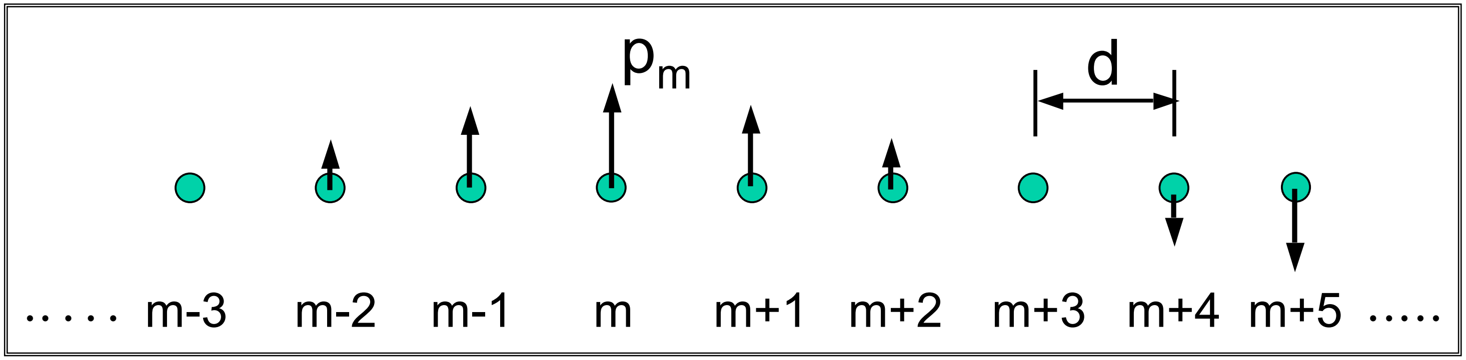


On resonance



C. F. Bohren, D. R. Huffman, Absorption and Scattering of Light by Small Particles, Wiley, New York 1983

Properties of a Chain of Metal Nanoparticles



- Near-field interaction sets up dipole (plasmon) waves
- Two types: Transverse (T) & Longitudinal (L) modes
- Interaction strength related to dipole field E_P

$E_P = E_F + E_M + E_R$ Where

$E_F \propto R^{-3}$ Förster field

$E_M \propto R^{-2}$

$E_R \propto R^{-1}$ Radiation field

When $d \ll \lambda$ Förster field dominant ⇨ n.n. interaction dominates

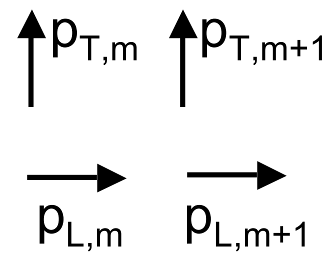
Dispersion Relation for Plasmon Modes

Equation of motion of dipole at m:

$$\ddot{p}_{i,m}(t) = -\omega_0^2 p_{i,m}(t) - \gamma_i \omega_1^2 \left[p_{i,m-1}(t) + p_{m+1}(t)\right]$$

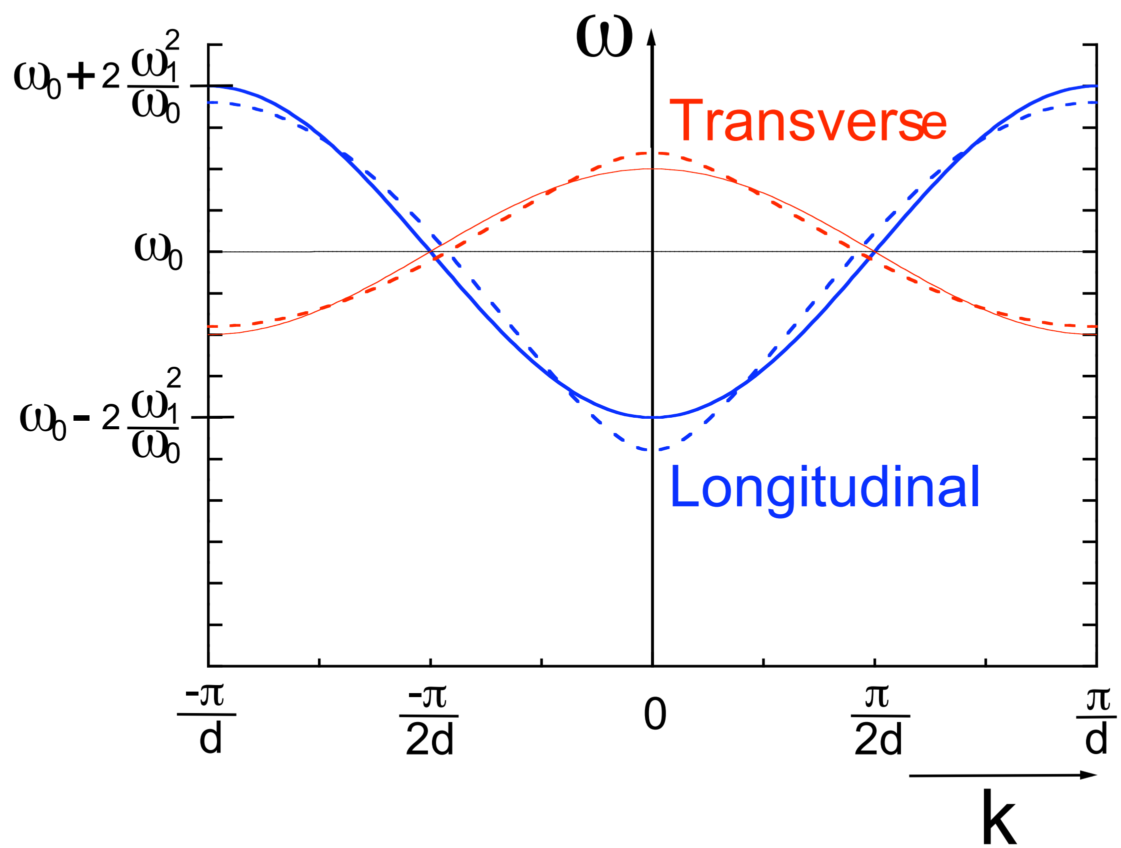
Where $\omega_1^2 = \dfrac{\rho V e}{4\pi\varepsilon_0 m_e n^2 d^3}$

$\gamma \equiv$ a polarization dependent constant $\begin{cases} \gamma_T = 1: \\ \gamma_L = -2: \end{cases}$



Propagating wave solution: $p_{i,m}(t) = P_i \exp i(\omega t \pm kmd)$

Dispersion Relation for Plasmon Modes



[illegible]

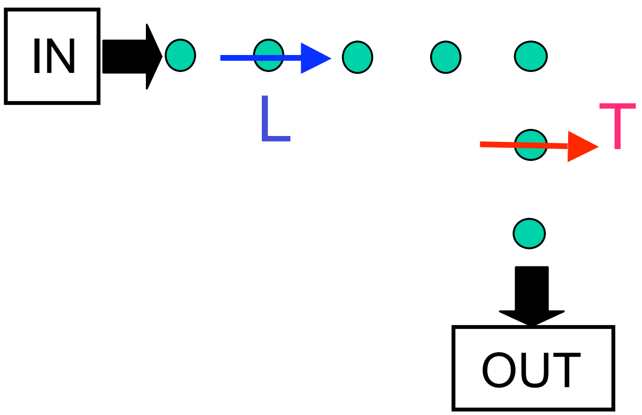
Where $\omega_1^2 = \frac{\rho V e}{4\pi\varepsilon_0 m_e n^2 d^3}$

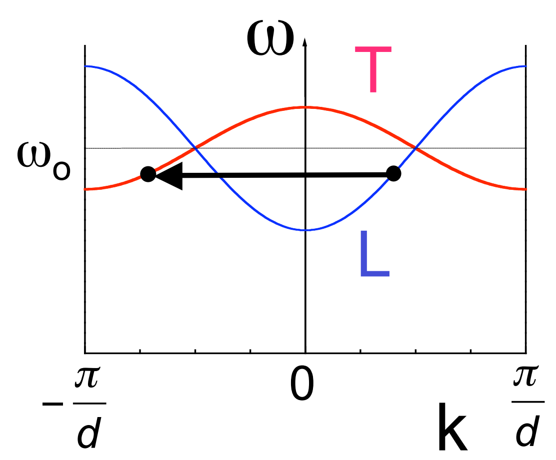
[illegible]

Example: Ag particles, R = 10 nm
d = 40 nm; n = 1.5

⇨ $v_{g,T}$ = 3.4 x 10^6 m/s
$\Delta\omega_T$ = 1.8 x 10^{14} s^{-1} (E = 115 meV)

Propagation Through Corners



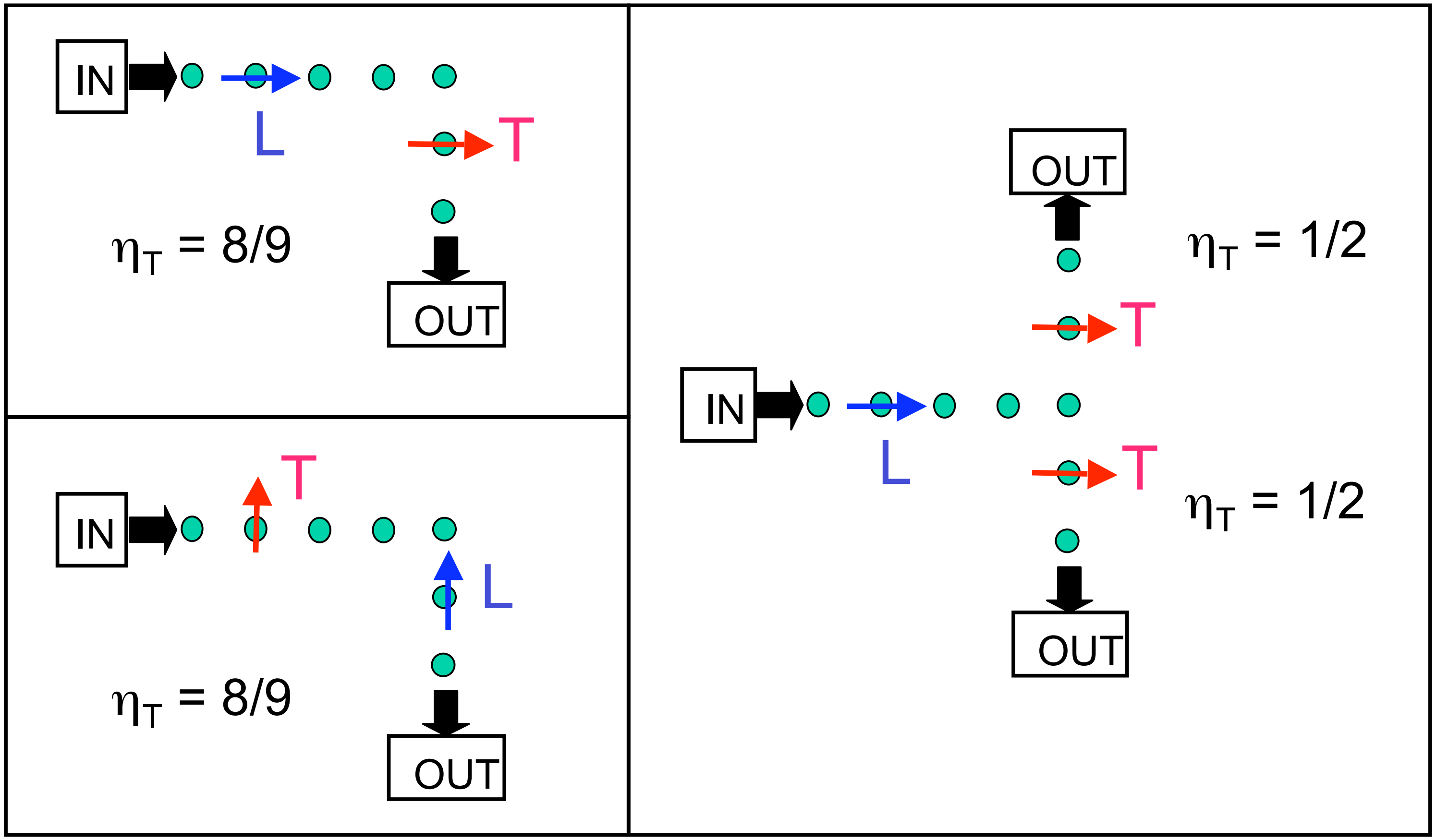


Calculation of power transmission coefficient, η_T (ω, pol):

- Continuity amplitude of plasmon wave
- Continuity energy flux in plasmon wave

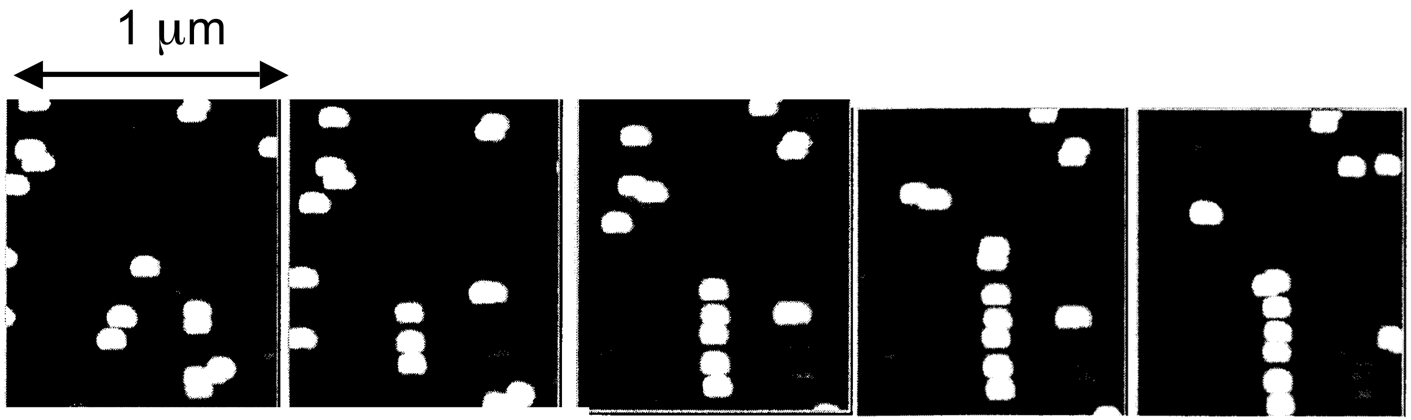
Maximum η_T at ω_0

Power Transmission Coefficients, η_T



- η_T > 64 % for all possible corner and T structures
- Calculations easily extended to 3D structures

Fabrication of Arrays by AFM Manipulation

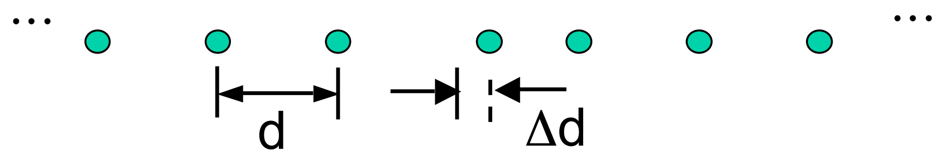


- AFM manipulation of 30 nm Au particles on APTS coated SiO_2
  (APTS = AminoPropylTrimethoxySilane)
- Advantages: Au particles and chemicals commercially available.
  Flexibility to image and modify structures.

Sheffer Meltzer, Aristides A.G. Requicha, and Bruce E. Koel, USC

The Role of Defects and Disorder ⇨ Reflections

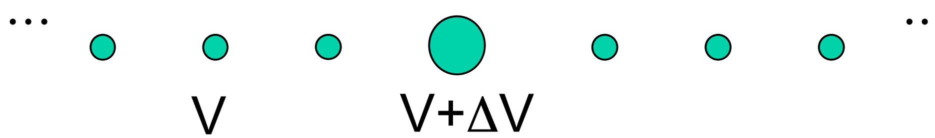
Periodicity



Dipole approximation: $\eta_T = 1 - 9(\Delta d/d)^2$

Example: $\Delta d/d$ = 5% (5nm/75nm) ➡ η_T = 96 %

Size fluctuations



Dipole approximation: $$\eta_T = \frac{1}{[1+\Delta V/2V)]^2}$$

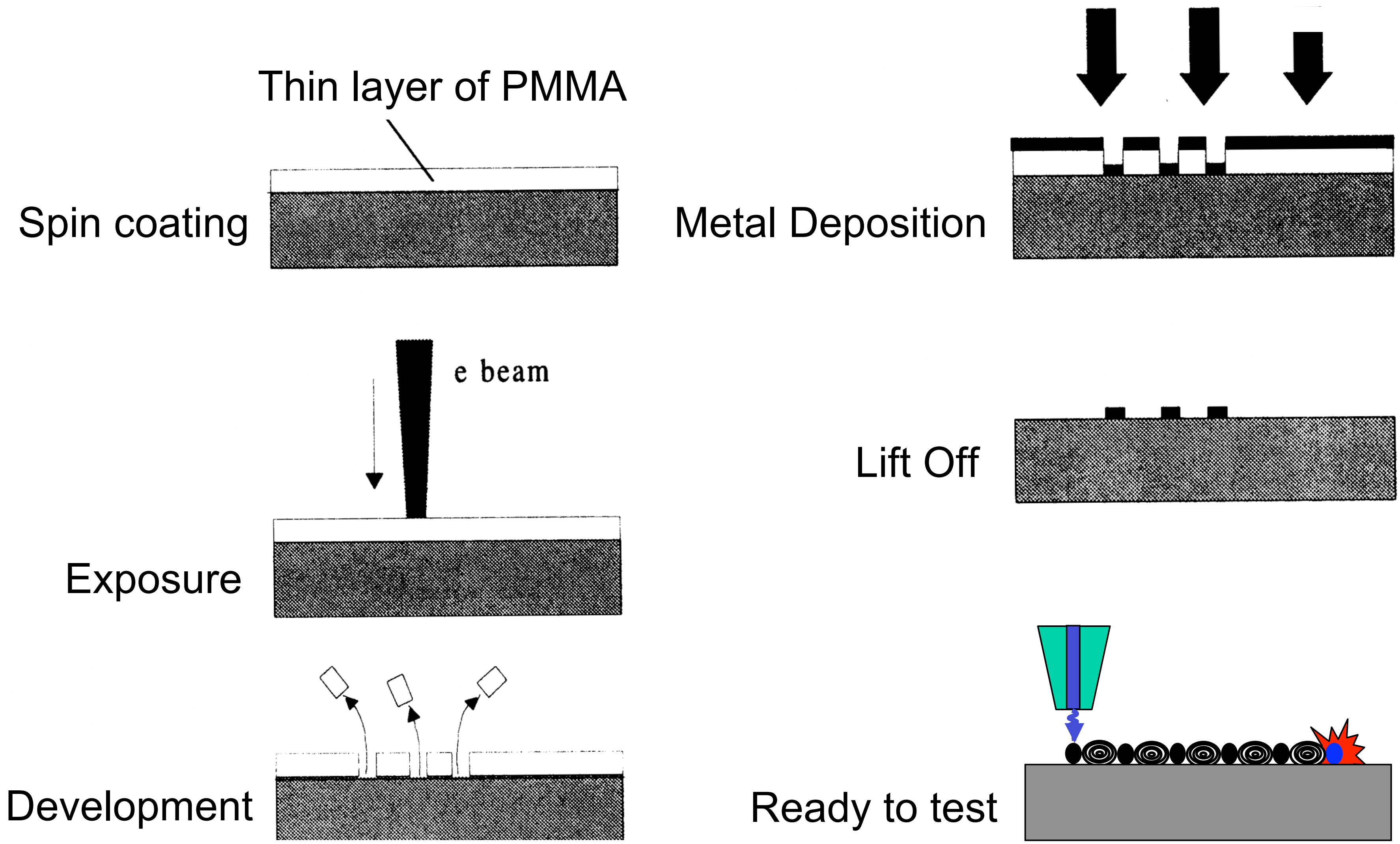
Example: $\Delta V/V$ = 9% (1nm/25nm) ➡ η_T = 91 %

Intrinsic loss:

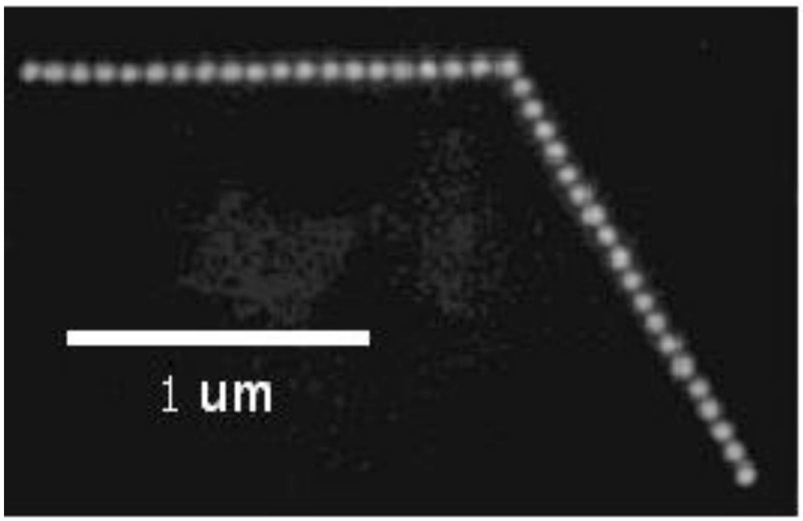
5% per interparticle spacing ➡ η_T = 95 %

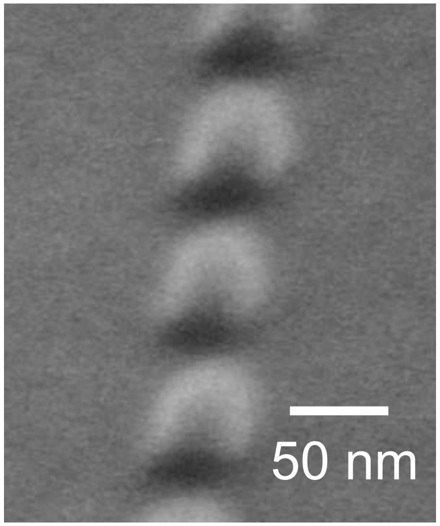
(Calculated for 25 nm Ag particles spaced by 75 nm)

Generation of Arrays by e-beam Lithography



SEM Images of Nanoparticle Arrays

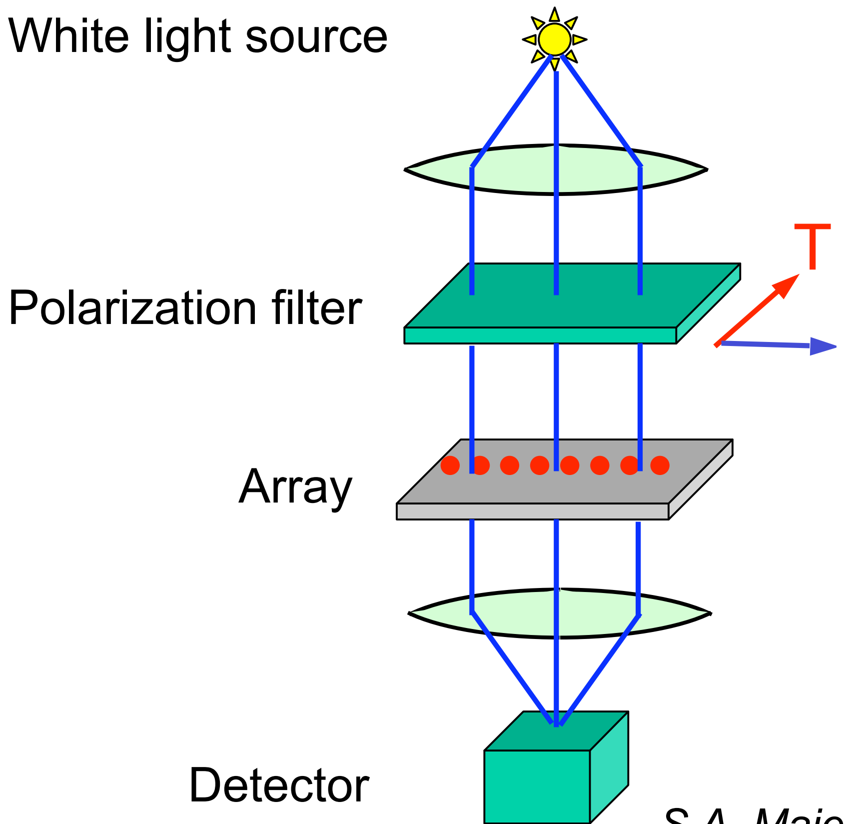


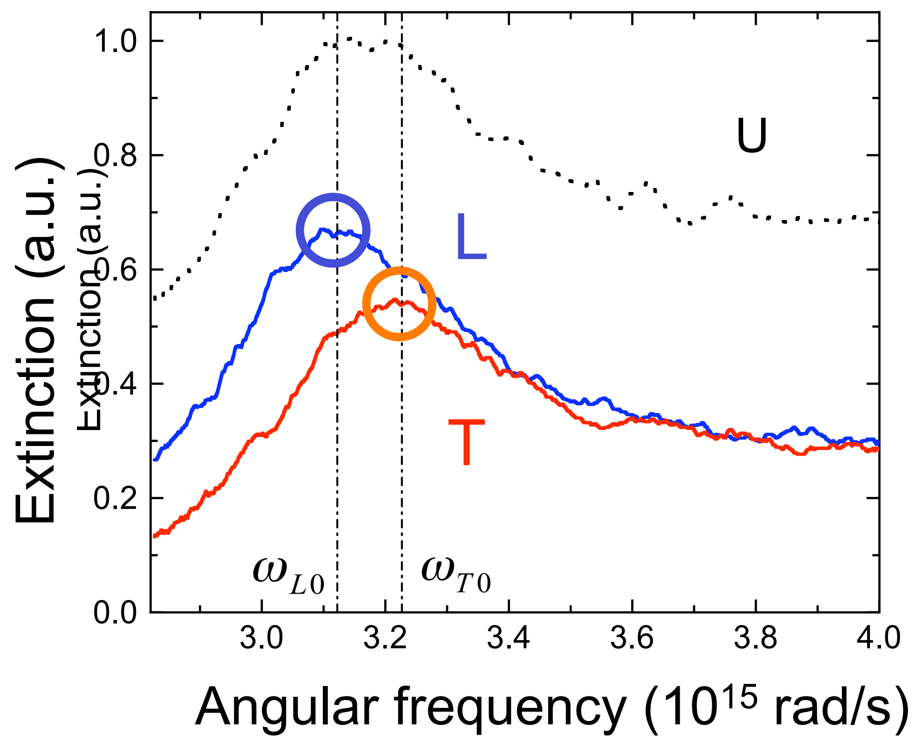


- Array of 50 nm diameter Au dots spaced by 75 nm
- Good control over particle size, shape, interparticle spacing

Far-field Spectroscopy on a Au Nanoparticle Array

Extinction measurement

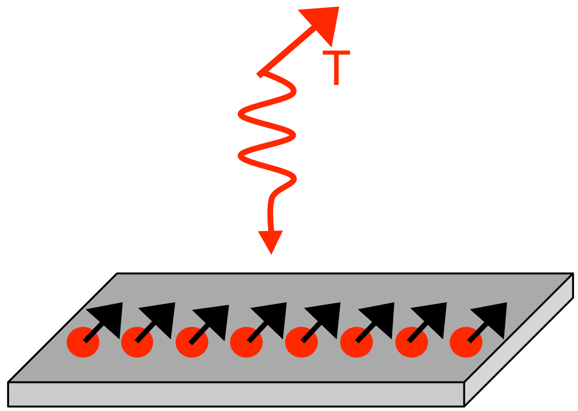




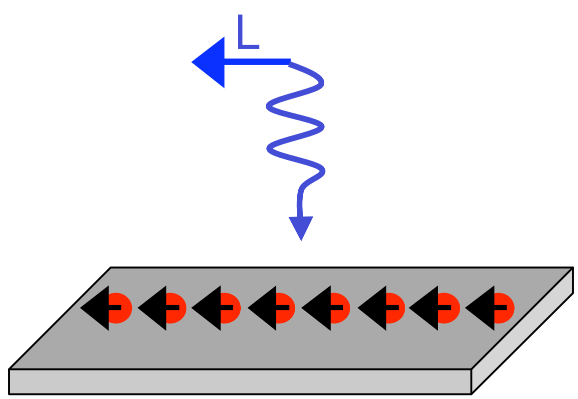
S.A. Maier et. al, Phys. Rev. B 65, 193408-193411 (2002).

- EM coupling between particles breaks the rotational symmetry of a single particle

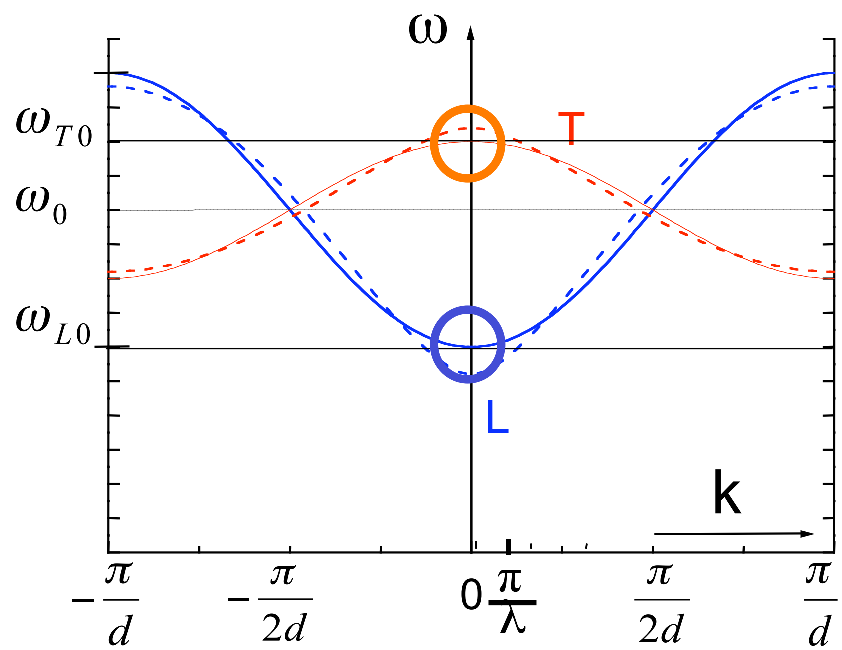
Observation of Near-field Coupling in Particle Arrays



Transverse polarization



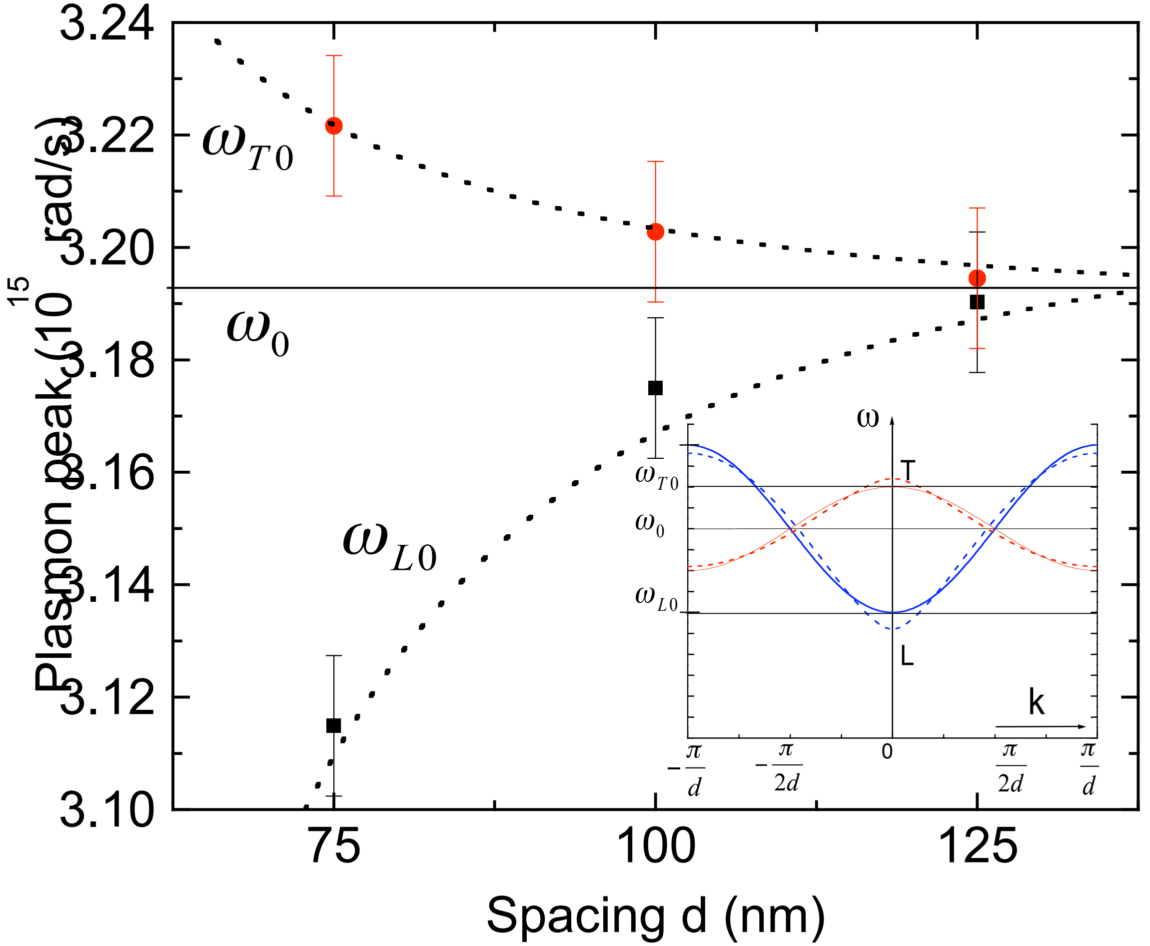
Longitudinal polarization



- Probes dispersion relation at **k**=0

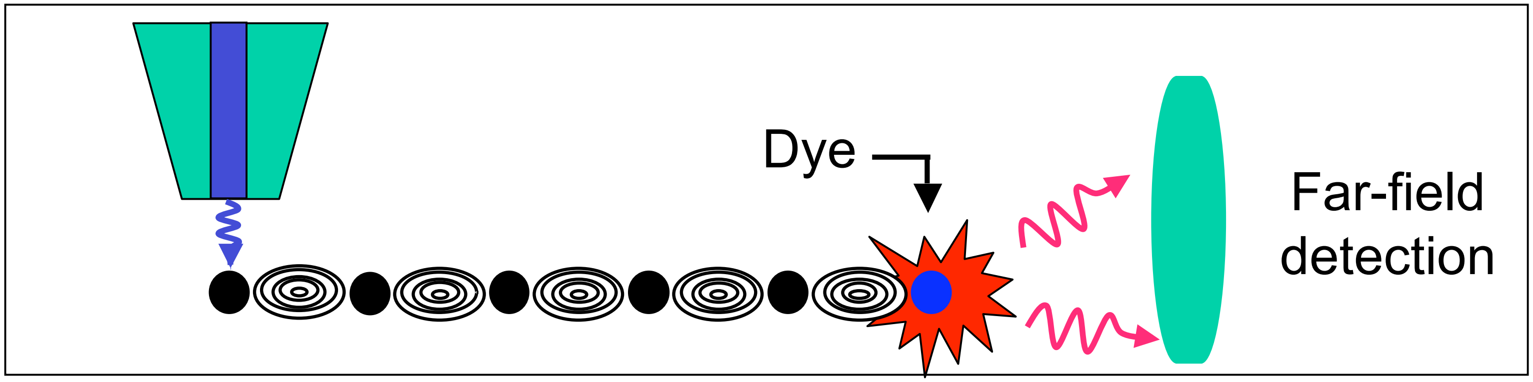
(Because λ >> d = interparticle spacing)

Dependence of Mode Splitting on Interparticle Spacing



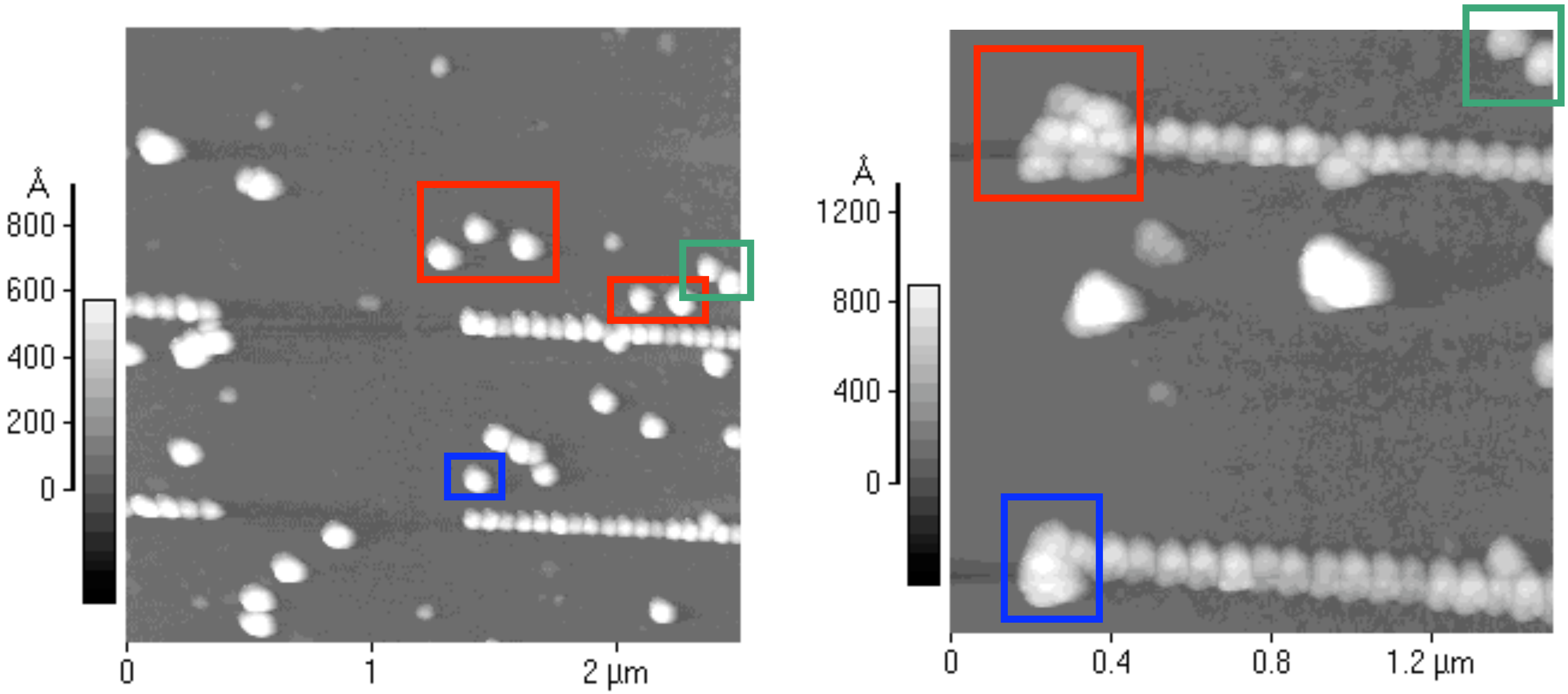
- Peak splitting vanishes with increasing interparticle spacing *d* as d^{-3}

Experiments on AFM Assembled Arrays



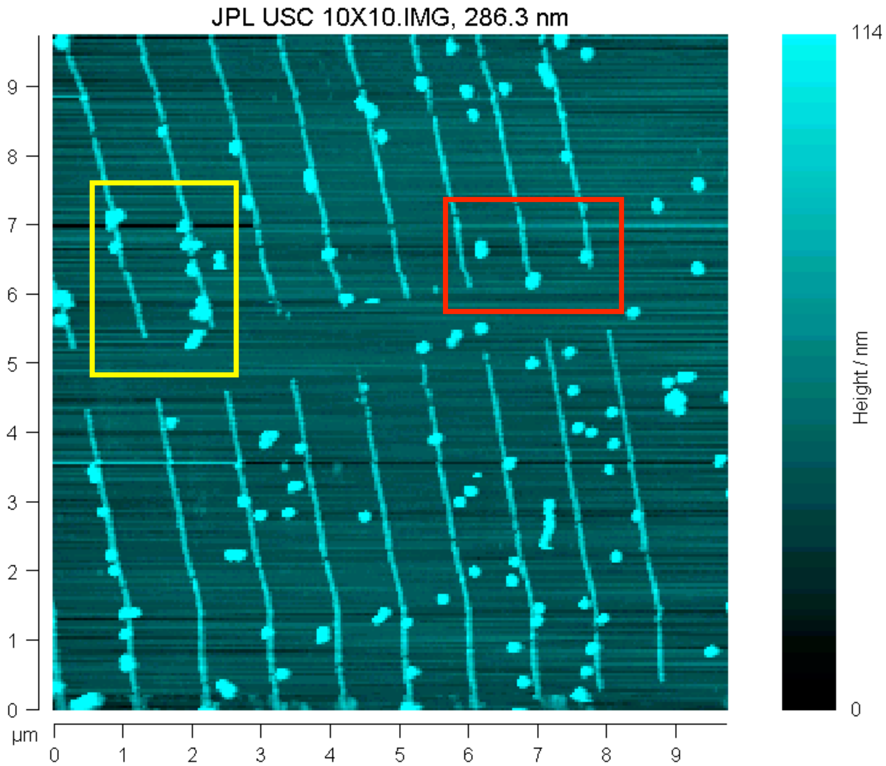
- Excitation using a scanning near-field optical microscope
- Transport along metal nanoparticle array
- Detection of dye luminescence in far-field

AFM Manipulation of Latex Beads with Dyes

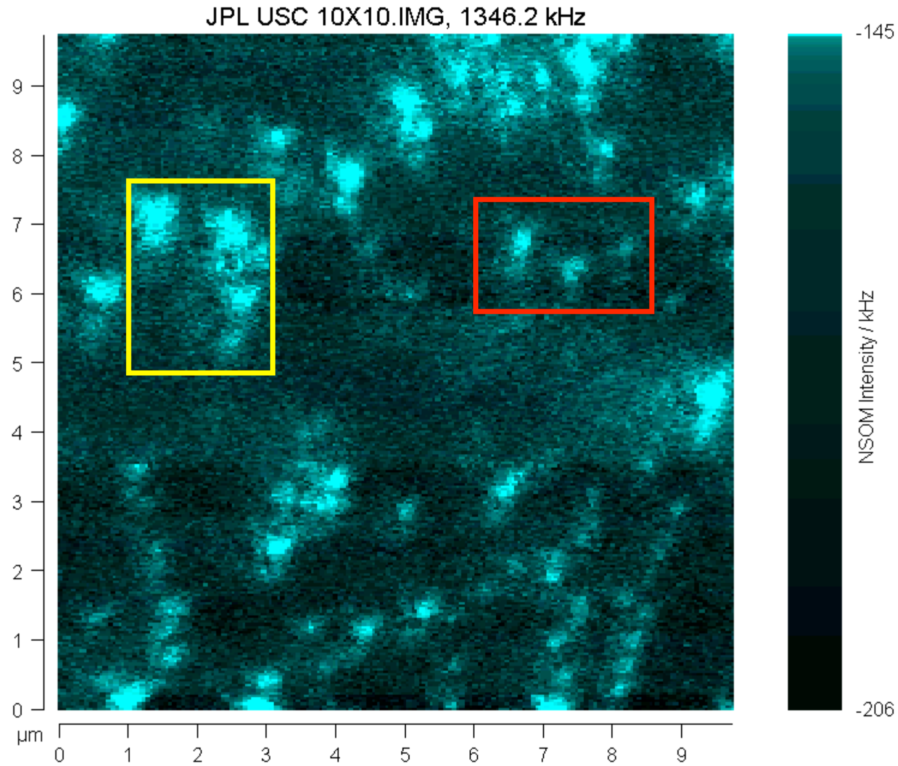


Luminescence from Single Latex Spheres

Topography

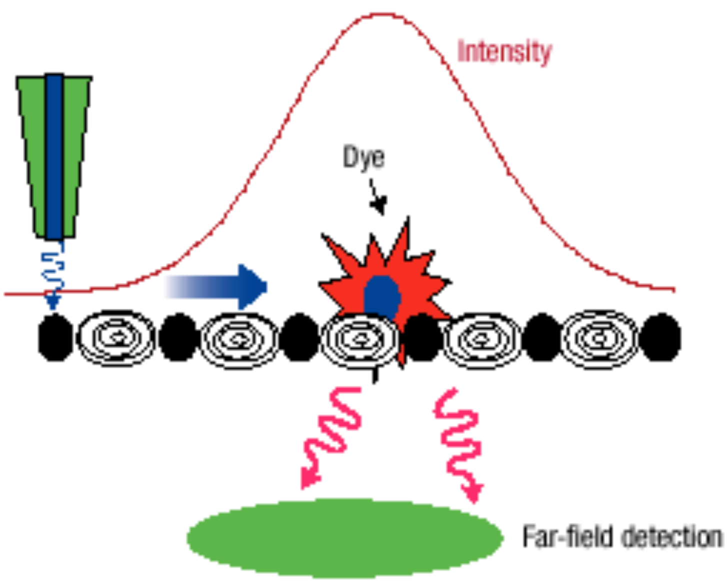


Fluorescence (inverted log)



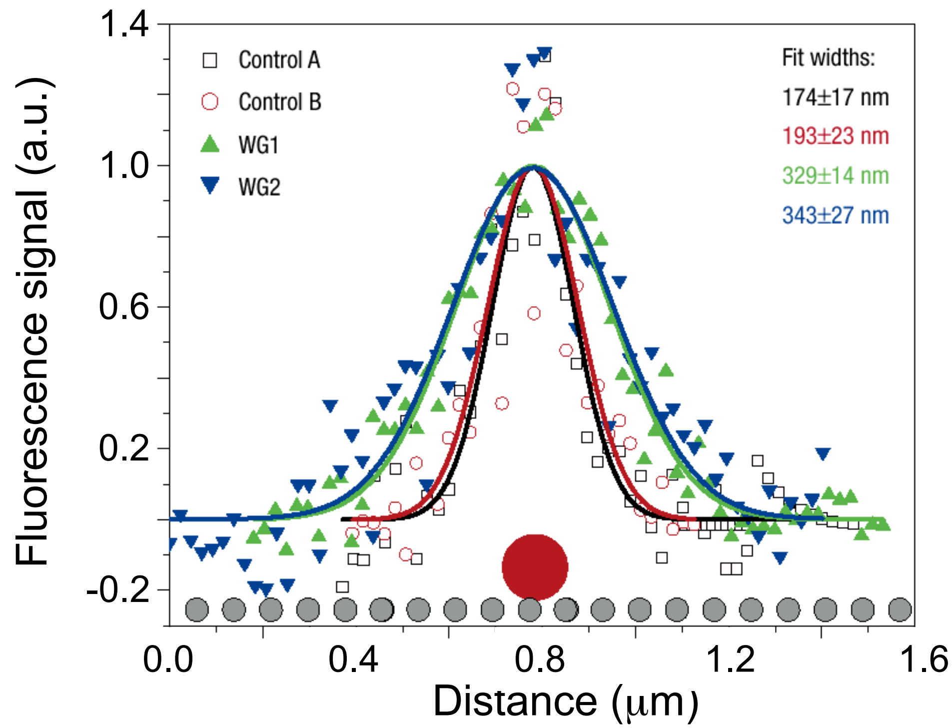
Transport experiment

Idea



If no transport occurs, fluorescence will only be collected when the tip is directly on top of the dye

Experiment



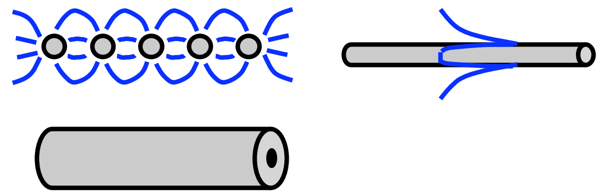
Green/blue curves luminescent particle on a wire
Red/black curves luminescent particles next to a wire

S.A.Maier, PhD Thesis CalTech 2003

The Future of Metal Optics

Photonics

• Basic building blocks



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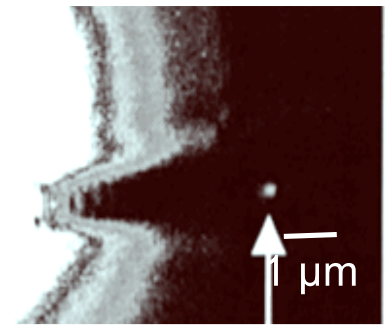
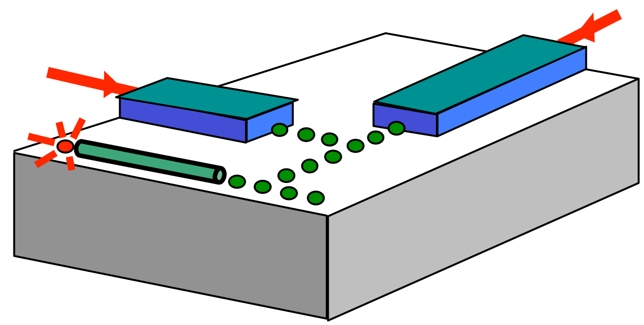


• More complex architectures



• Applications in biology for “Optical microscopy” ?

• Applications in high-density optical data storage ?

• Fundamental studies of light-matter interaction

** R.M. Dickson et al., J. Phys. Chem. B* ***104****, 6095-6098 (2000)*

The Future of Metal Optics

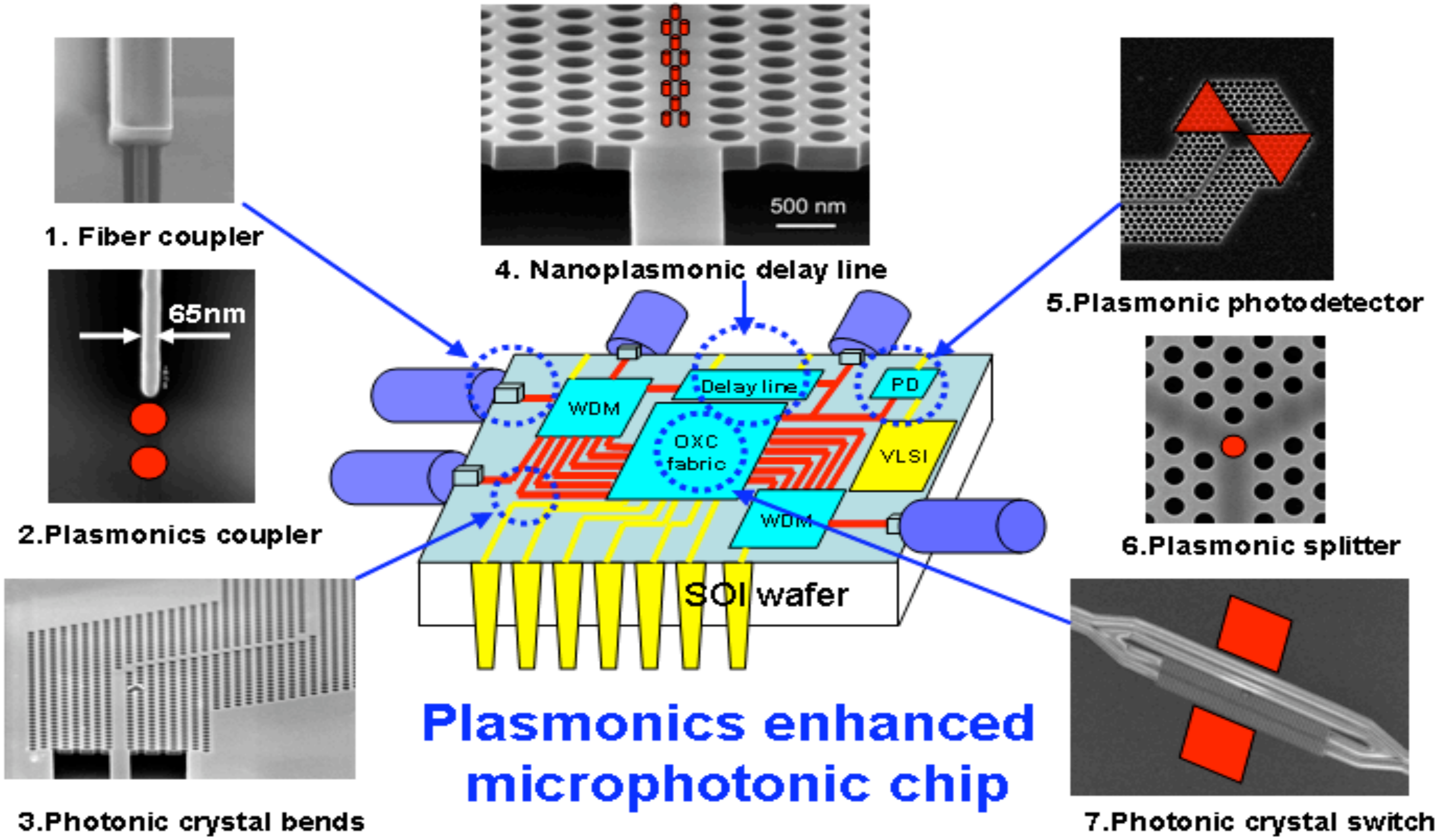
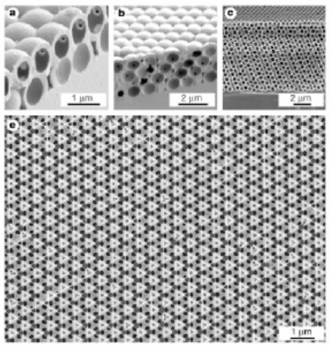
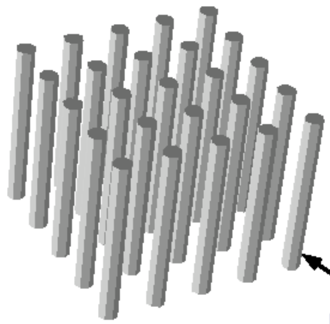


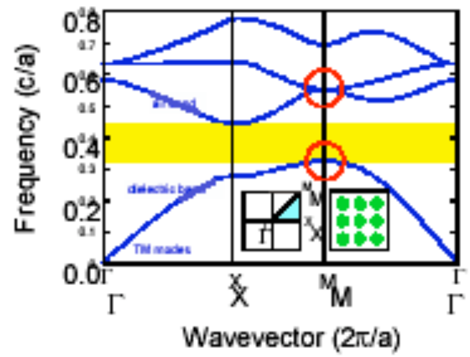
Fig 1. Integration of plasmonic elements onto Si-based microphotonic chips. SEM images are of actual photonic devices (**Vlasov**).

Addition to Lecture #11: Localization and Guiding of Surface Plasmon Polaritons in Random Nanostructures

Bozhevolnyi et al., Physics Review Letter 89, p186801-1 ***(2002)***

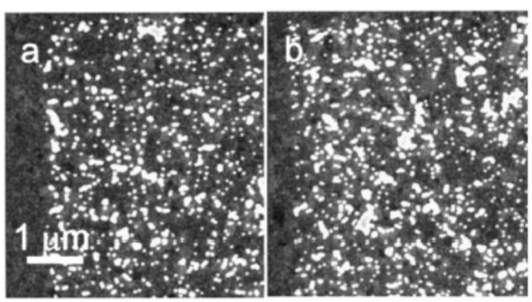
Ordere  nic b

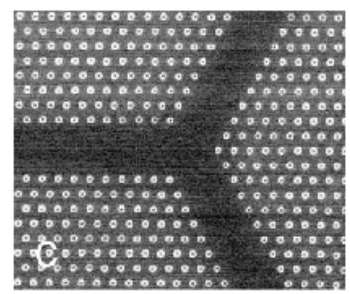




$l \approx \lambda / 2$

Disordered media: localization (multiple scattering)

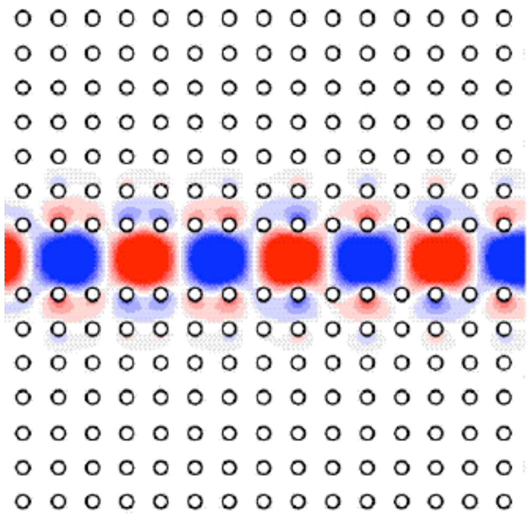




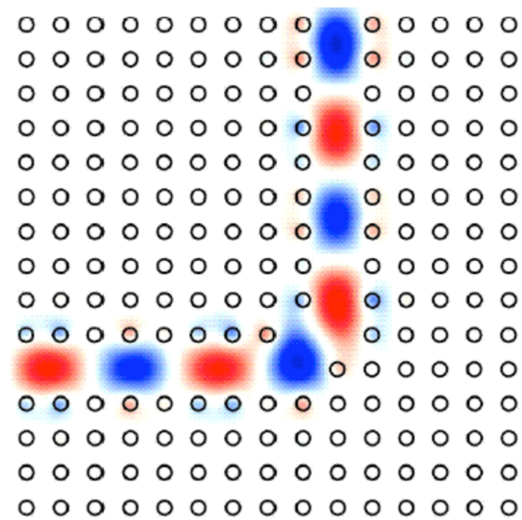
$l < \lambda / 2\pi$

- Both inhibit light propagation
- Both in a limited range of frequencies
- Both require a large refractive index contrast

Photonic crystals confine the light inside the defect



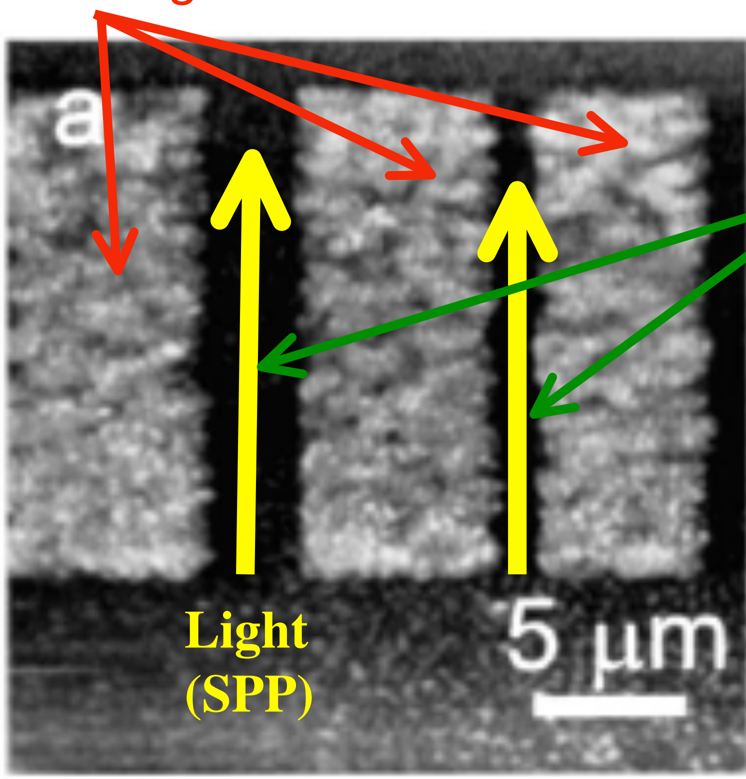
Can guide light through bends!



Can the same thing can be done in random media?

This paper: First observations of confinement due to random corrugations created by surface features.

Surface corrugation

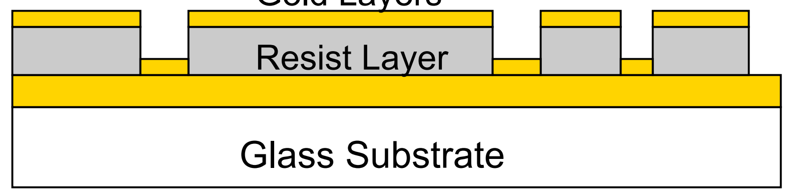


Propagation of SPPs: Surface Plasmon Polariton

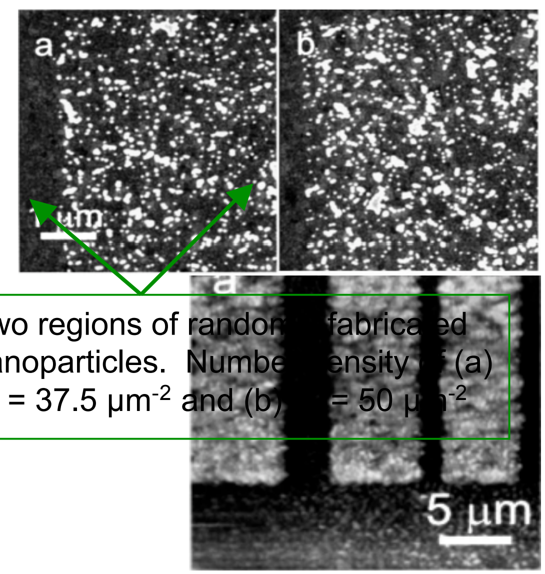
Confining mechanism: ***localization***, i.e. multiple scattering and interference that prevents the light from propagating.

Randomly positioned Au nanoscatterers lead to strong SPP localization

- 45 nm thick Au layer thermally evaporated onto glass substrate
- Resist is deposited on Au layer and 6 x 18 μm² rectangular areas patterned
- Random coordinates within each rectangle exposed using an electron beam
- Exposed region removed and 2nd Au layer evaporated
- Remaining resist is etched away leaving disordered arrays of ~45 nm high gold bumps



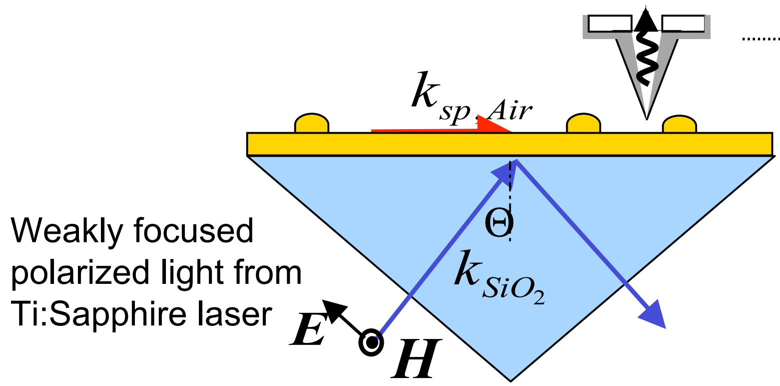
A 2- and 4-μm wide channel were left free of scatterers for SPP guiding



Two regions of randomly fabricated nanoparticles. Number density of (a) n_1 = 37.5 μm^{-2} and (b) n_2 = 50 μm^{-2}

*Bozhevoloyi, et al., Physical Review Letters, 86 (**2001**)*

Kretchmann-based configuration used to excite SPP's



MSE 346 Course Notes

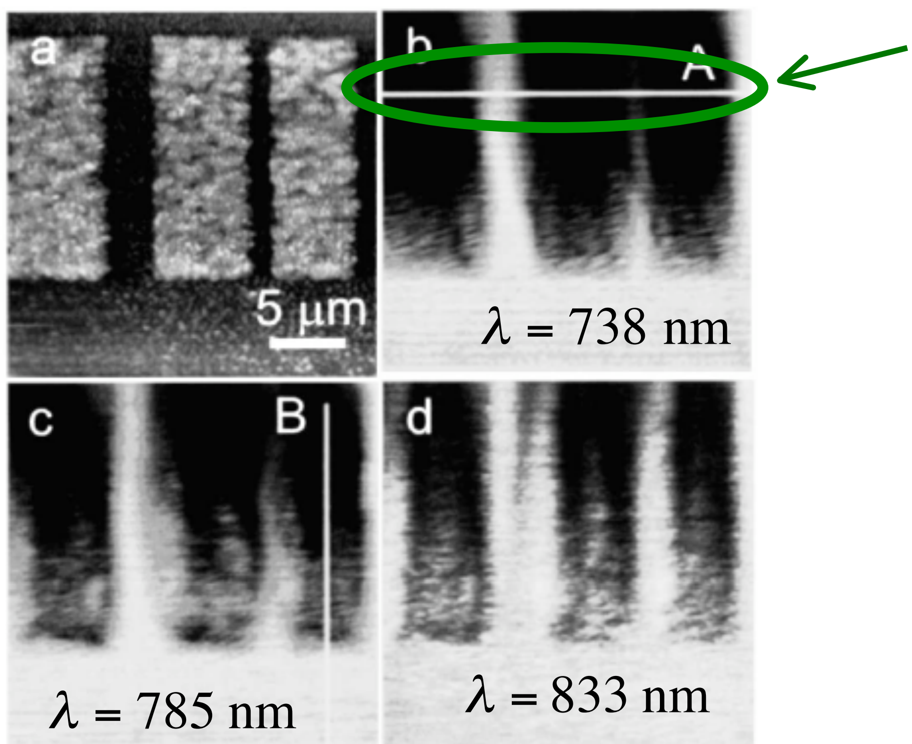
http://www.elicht.com/DualScop.htm

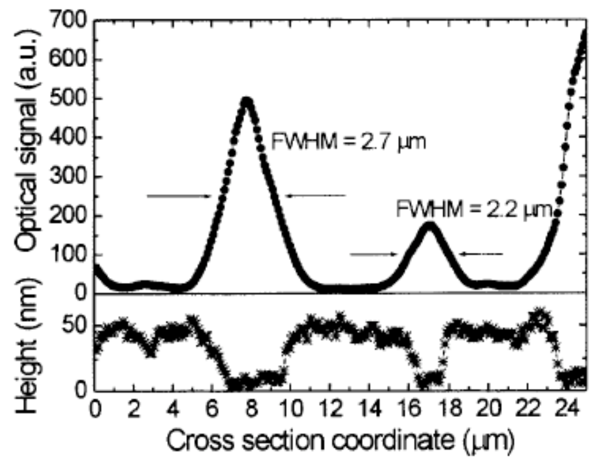
- Ti:Sapphire laser (λ = 725 – 850 nm, P~100 mW) excitation source focused to a 300 μm spot size

- Near-field radiation scattered by sharp fiber tip into fiber modes. Imaged by DME-DualScope NSOM

- SPP excitation recognized through a minimum in the angular dependence of reflected light

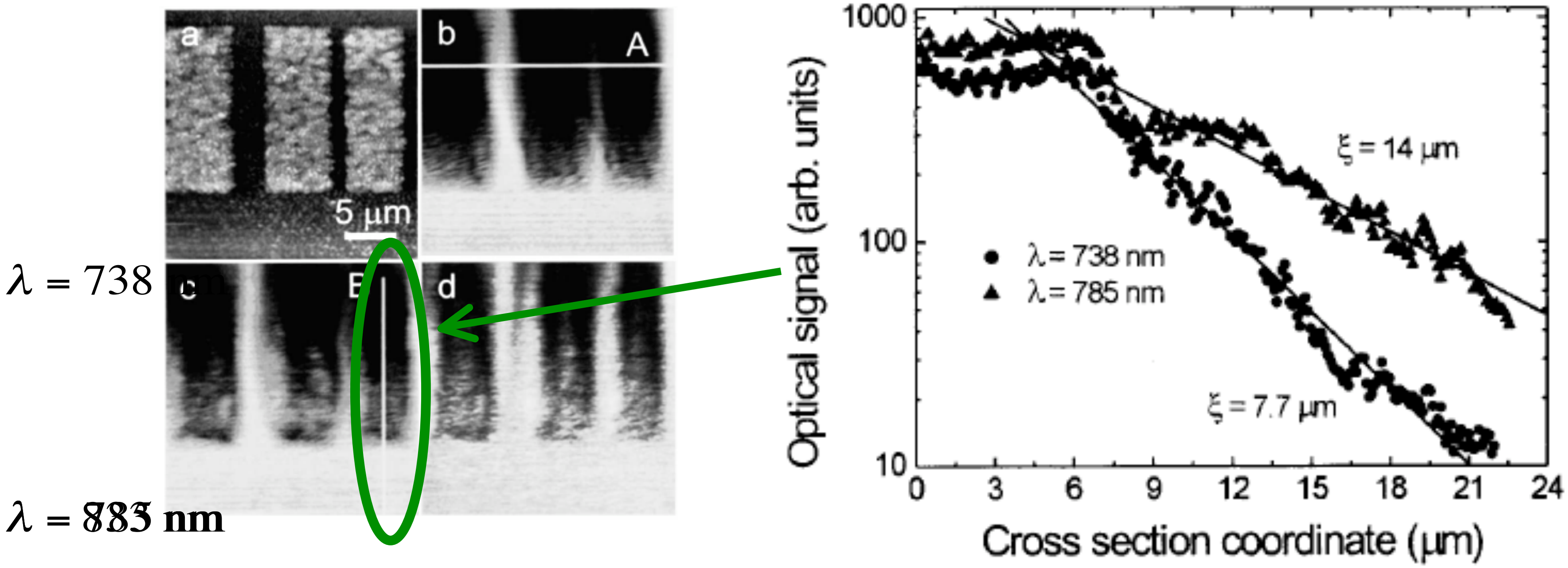
Experimental demonstration of waveguiding





- Waveguide length: 18 µm
- Waveguiding range:
  725 - 765 nm
  (40 nm bandwidth!)

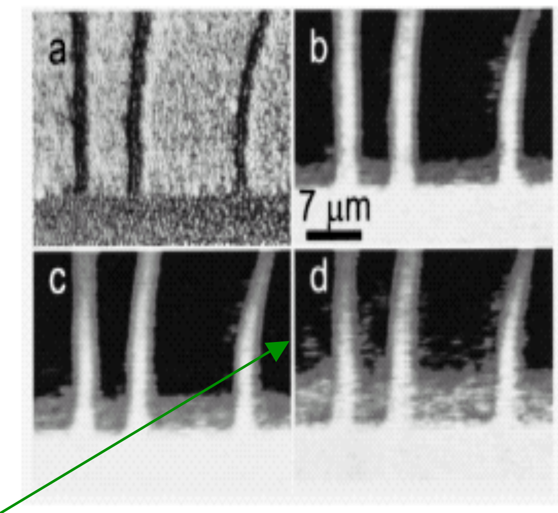
Random media stops the propagation of the light



The penetration depth (or localization length) depends on the scattering cross-section, the scattering mean free path, and the wavelength

Future Work

- Increase particle number density
  (75 per μm^2 has been tried and works better)
- Increase the particle size
  (for a larger scattering cross-section)
- Bends and other waveguide geometries



2-μm straight and bent channels show strong SPP attenuation. Low levels of additional bend loss (<1dB) in the wavelength range of 735-795 nm

- Successful demonstration of waveguiding of surface plasmon-polaritons
- Demonstration of confinement in disordered media
- Random media could perhaps complement photonic crystals in future work…