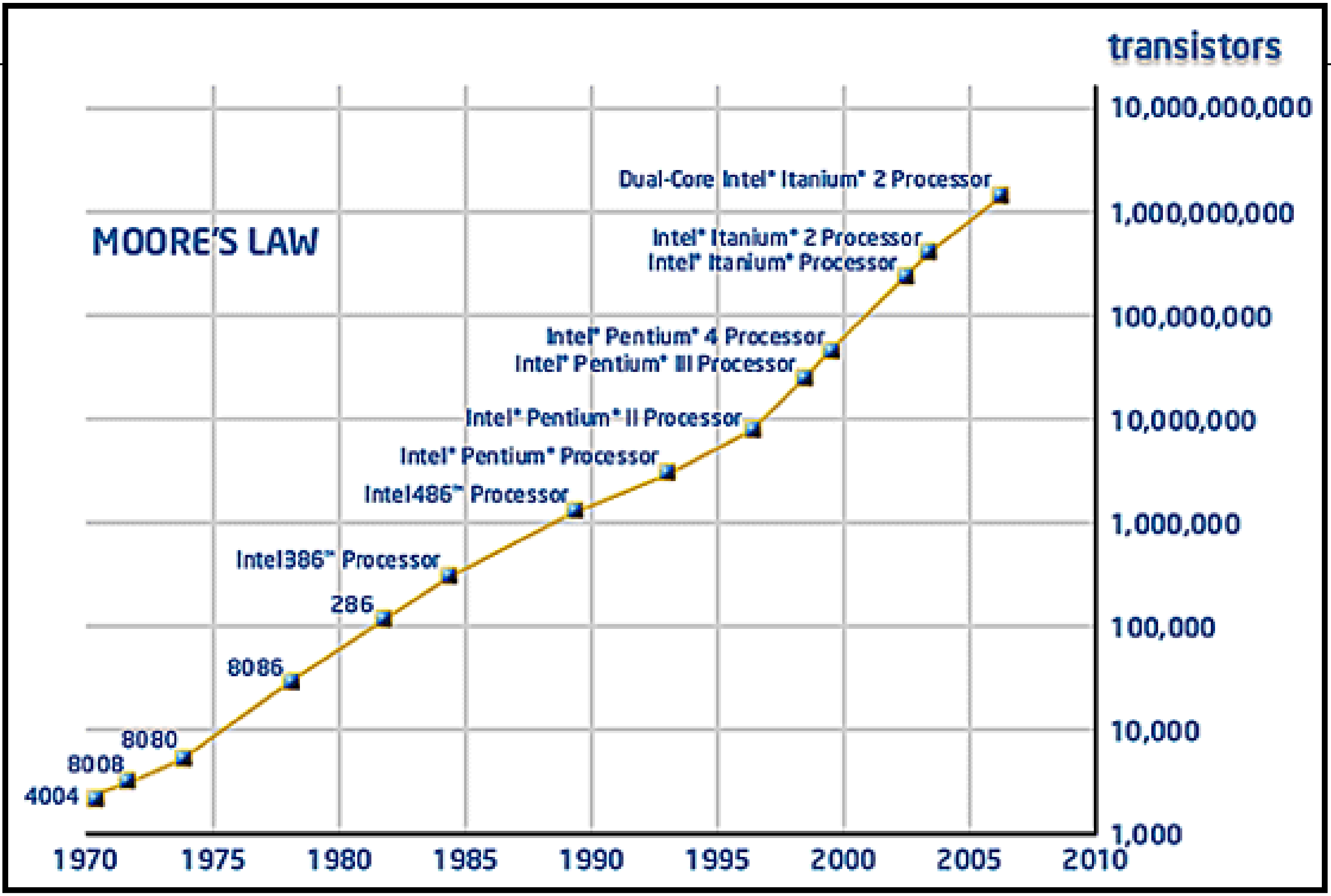
Part 2:
Plasmonic Nanophotonics

Motivation – Device densities



www. intel.com

- **Device densities are exponentially increasing**

Why not electronics?

As **data rates** AND component packing **densities** INCREASE, electrical interconnects become progressively limited by ***RC***-delay:

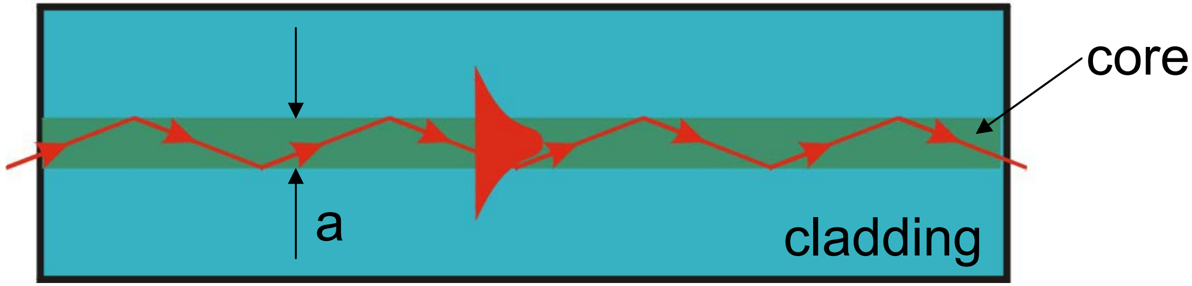
$$R \propto L/A \quad \oplus \quad C \propto L \quad \Rightarrow \quad B_{\max} \propto \frac{1}{RC} \propto \frac{A}{L^2}$$

$$\Rightarrow B_{\max} \leq 10^{15} \times \frac{A}{L^2} \ \ (\text{bit/s})(A << L^2 \,!)$$

Electronics is aspect-ratio *<u>limited in speed</u>*!

Why not photonics?

The bit **rate** in optical communications is fundamentally limited **only** by the carrier frequency: $B_{max} < f \sim 100$ Tbit/s (!), but **light propagation is subjected to diffraction:**



$$n_{core} = n_{clad} + \delta n = n + \delta n \Rightarrow V = \frac{2\pi}{\lambda} a \sqrt{n_{core}^2 - n_{clad}^2} \cong \frac{2\pi}{\lambda} a\sqrt{2n\delta n}$$

$$\text{well-guided mode}: V \propto \pi \Rightarrow a \cong \lambda / 2\sqrt{2n\delta n} \ - \text{mode size}: \delta n << 1(!)$$

Photonics is diffraction- *limited in size*!

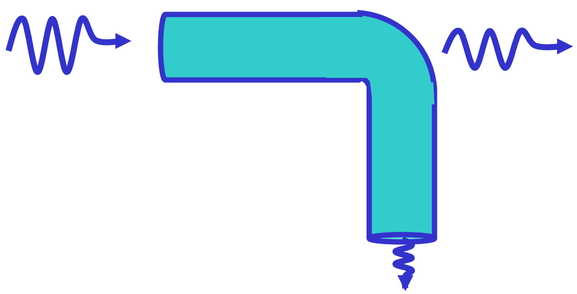
Metal Optics: An Introduction

Majority of optical components based on dielectrics

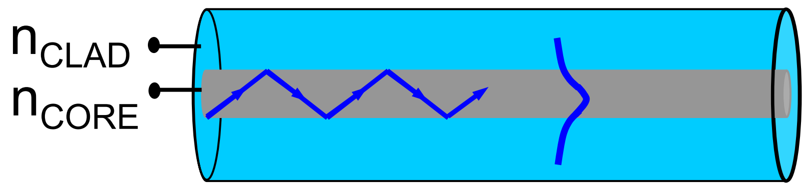
- High speed, high bandwidth (ω), but…
- Does not scale well ⇨ Needed for large scale integration

Problems

Bending losses



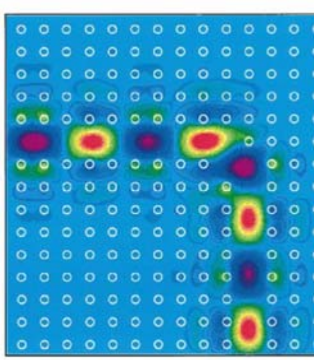
Diffraction Limit



Optical mode in waveguide > $\lambda_0/2n_{CORE}$

Solutions ?

Some:



J. D. Joannopoulos, et al, Nature, vol.386, p.143-9 (1997)

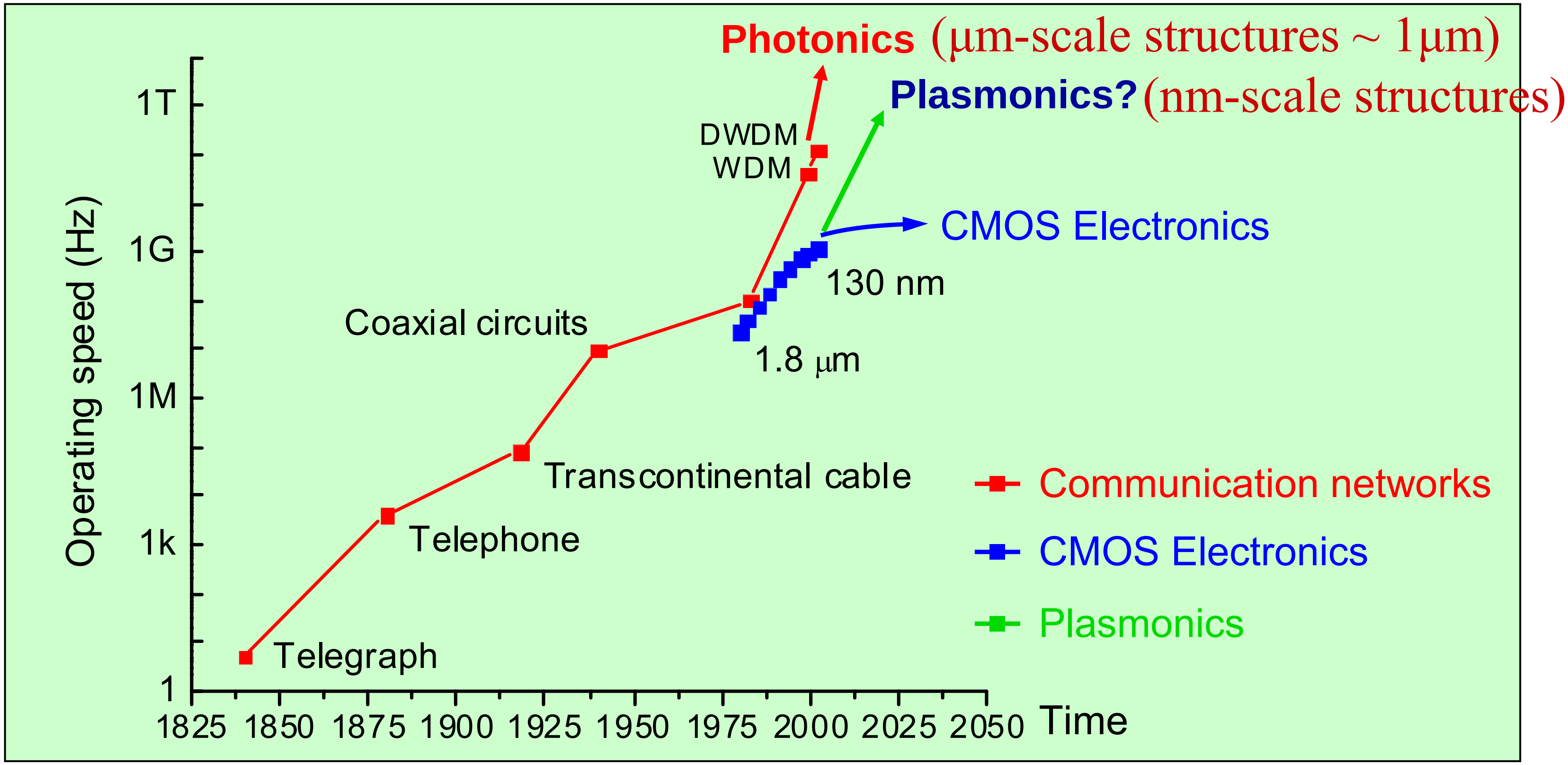
Some fundamental problems!

⇩

Photonic functionality based on metals?!

Nanophotonics with Plasmonics: A logical next step?

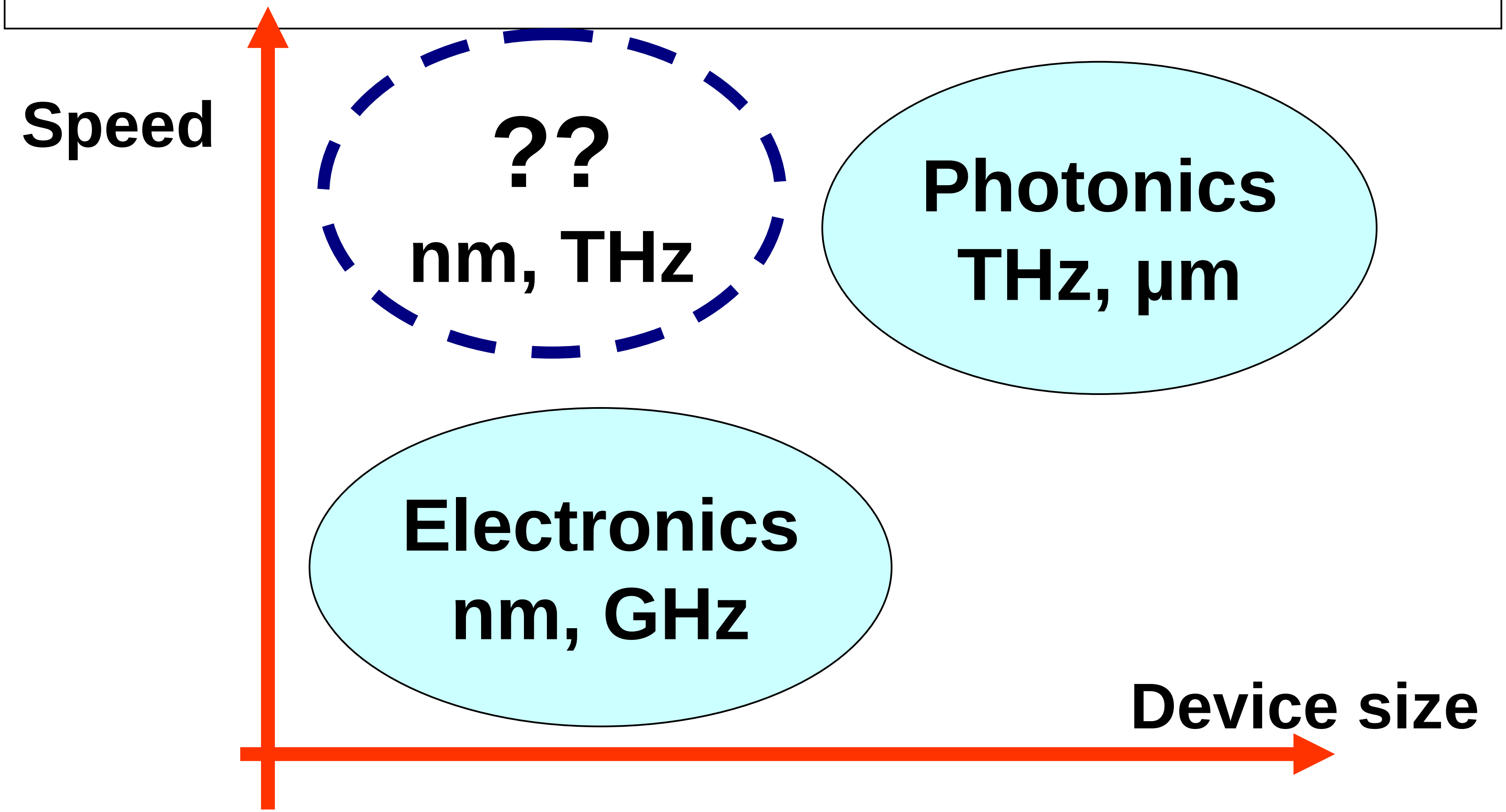
- The operating speed of data transporting and processing systems



- The ever-increasing need for faster information processing and transport is undeniable

- Electronic components are running out of steam due to issues with RC-delay times

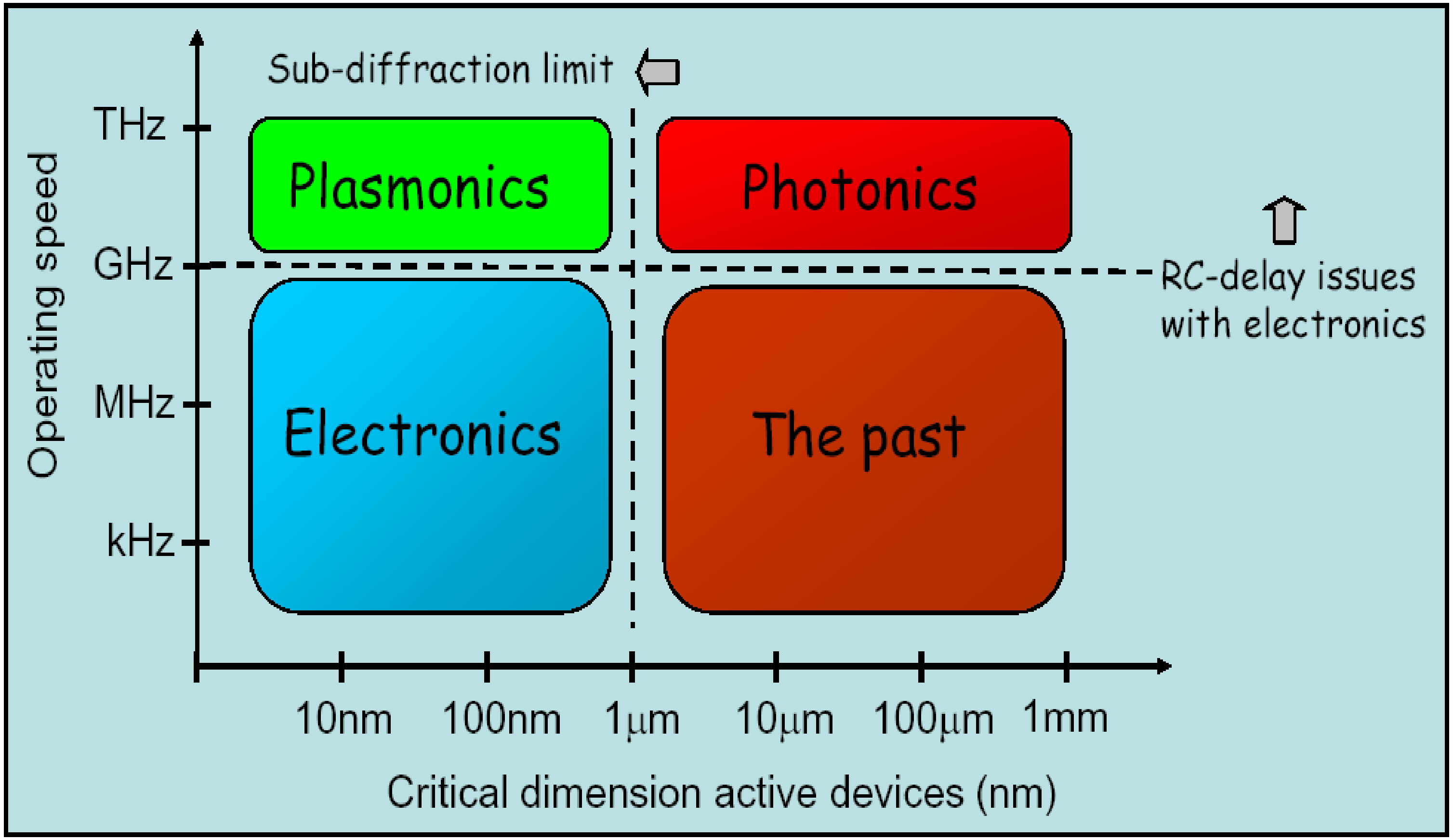
Motivation – nm scale THz speed



- **Something with best of both worlds?**

Why nanophotonics needs plasmons?

- Graph of the operating regimes of different technologies



- Plasmonics will enable an improved synergy between electronic and photonic devices
  - Plasmonics naturally interfaces with similar size electronic components
  - Plasmonics naturally interfaces with similar operating speed photonic networks

Courtesy of M. Brongersma

Optical Properties of an Electron Gas (Metal)

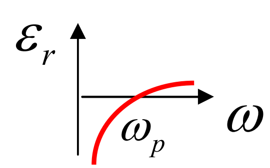
Dielectric constant of a free electron gas (no interband transitions)

- Consider a time varying field: $\mathbf{E}(t) = \mathrm{Re}\{\mathbf{E}(\omega)\exp(-i\omega t)\}$
- Equation of motion electron (no damping): $m\frac{d^2\mathbf{r}}{dt^2} = -e\mathbf{E}$
- Dipole moment electron: $\mathbf{p}(t) = -e\mathbf{r}(t)$

$$\Rightarrow m\frac{d^2\mathbf{p}}{dt^2} = e^2\mathbf{E}$$

- Harmonic time dependence: $\mathbf{p}(t) = \mathrm{Re}\{\mathbf{p}(\omega)\exp(-i\omega t)\}$
- Substitution **p** into Eq. of motion: $-m\omega^2\mathbf{p}(\omega) = e^2\mathbf{E}(\omega)$
- This can be manipulated into: $\mathbf{p}(\omega) = -\frac{e^2}{m}\frac{1}{\omega^2}\mathbf{E}(\omega)$
- The dielectric constant is:

$$\varepsilon_r = 1 + \chi = \frac{N\mathbf{p}(\omega)}{\varepsilon_0\mathbf{E}(\omega)} = 1 - \frac{Ne^2}{\varepsilon_0 m}\frac{1}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$$



Dispersion Relation for EM Waves in Electron Gas

Determination of dispersion relation for bulk plasmons

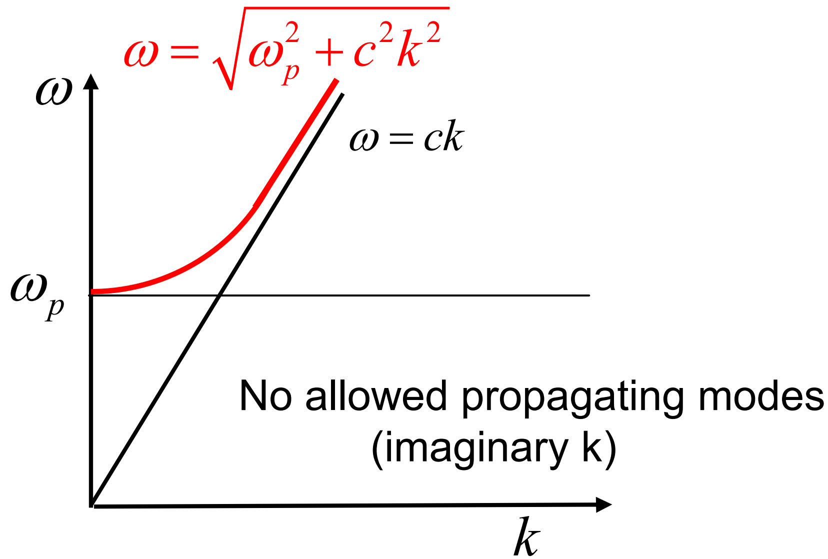
- The wave equation is given by: $$\frac{\varepsilon_r}{c^2}\frac{\partial^2 \boldsymbol{E}(\boldsymbol{r},t)}{\partial \boldsymbol{t}^2} = \nabla^2 \boldsymbol{E}(\boldsymbol{r},t)$$
- Investigate solutions of the form: $$\boldsymbol{E}(\boldsymbol{r},t) = \mathrm{Re}\left\{\boldsymbol{E}(\boldsymbol{r},\omega)\exp\left(i\boldsymbol{k}\cdot\boldsymbol{r} - i\omega t\right)\right\}$$

$$\Rightarrow \quad \omega^2 \varepsilon_r = c^2 k^2$$

- Dielectric constant: $\varepsilon_r = 1 - \dfrac{\omega_p^2}{\omega^2}$

$$\Rightarrow \quad \omega^2\left(1 - \frac{\omega_p^2}{\omega^2}\right) = \omega^2 - \omega_p^2 = c^2 k^2$$

- Dispersion relation:



Note1: Solutions lie above light line

Note2: Metals: $\hbar\omega_p \approx 10$ eV; Semiconductors $\hbar\omega_p < 0.5$ eV (depending on dopant conc.)

Plasmon-Polaritons

What is a plasmon ?

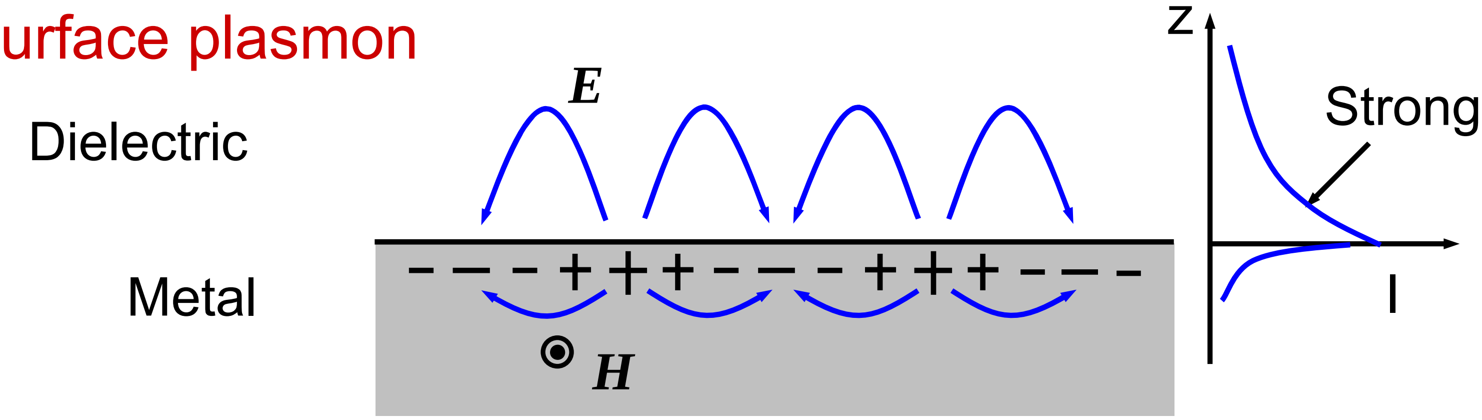
- Compare electron gas in a metal and real gas of molecules
- Metals are expected to allow for electron density waves: plasmons

Bulk plasmon

- Metals allow for EM wave propagation above the plasma frequency

They become transparent!

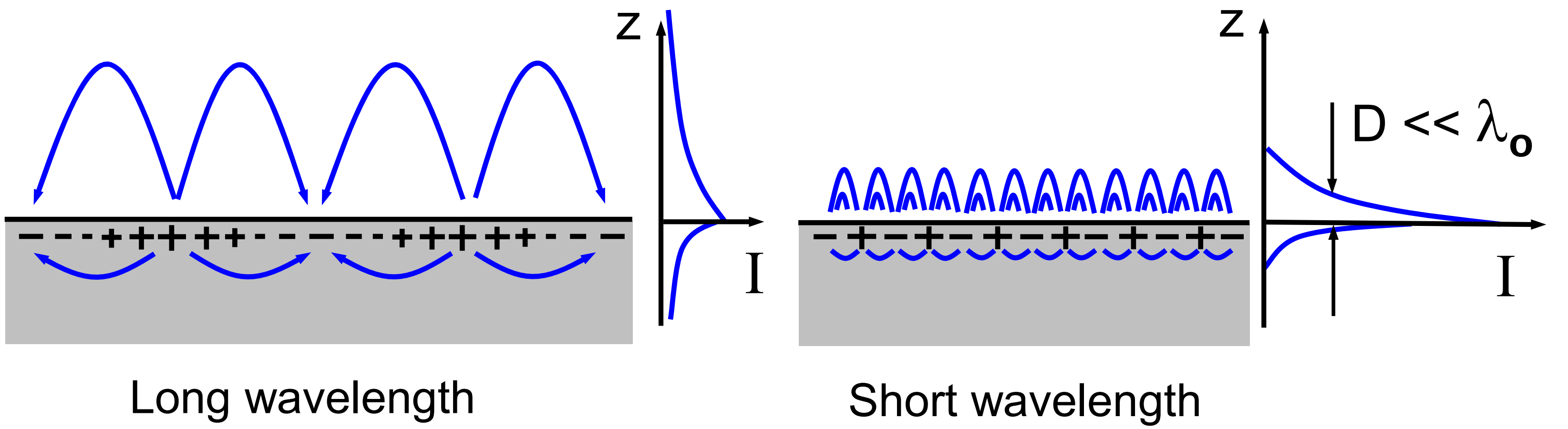
Surface plasmon



Note: This is a TM wave

- Sometimes called a surface plasmon-polariton (strong coupling to EM field)

Local Field Intensity Depends on Wavelength



Characteristics plasmon-polariton

- Strong localization of the EM field
- High local field intensities easy to obtain

Applications:

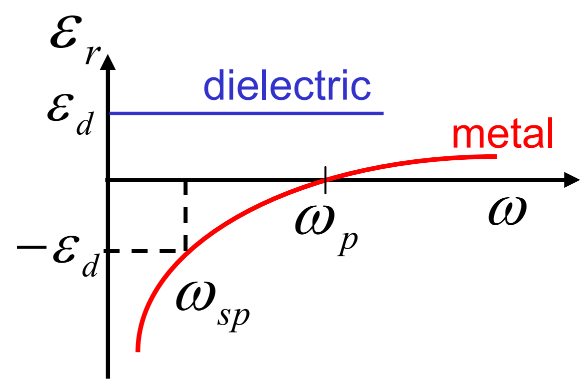
- Guiding of light below the diffraction limit (near-field optics)
- Non-linear optics
- Sensitive optical studies of surfaces and interfaces
- Bio-sensors
- Study film growth
- ……

Dispersion Relation Surface-Plasmon Polaritons

Plot of the dispersion relation

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

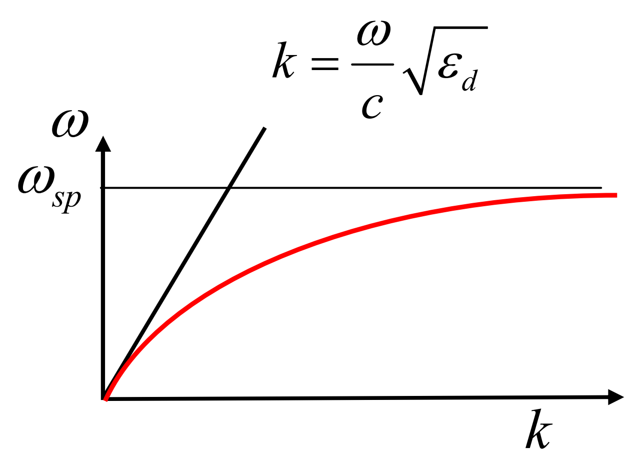
- Plot dielectric constants



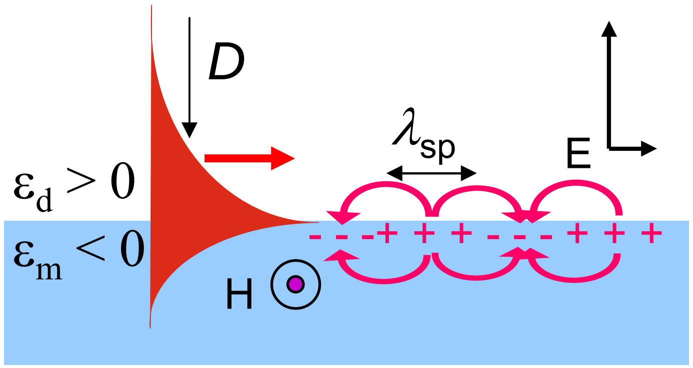
- Low ω: $k_x = \frac{\omega}{c}\lim_{\varepsilon_m \to -\infty}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2} \approx \frac{\omega}{c}\sqrt{\varepsilon_d}$

- At $\omega = \omega_{sp}$ (when $\varepsilon_m = -\varepsilon_d$): $k_x \to \infty$

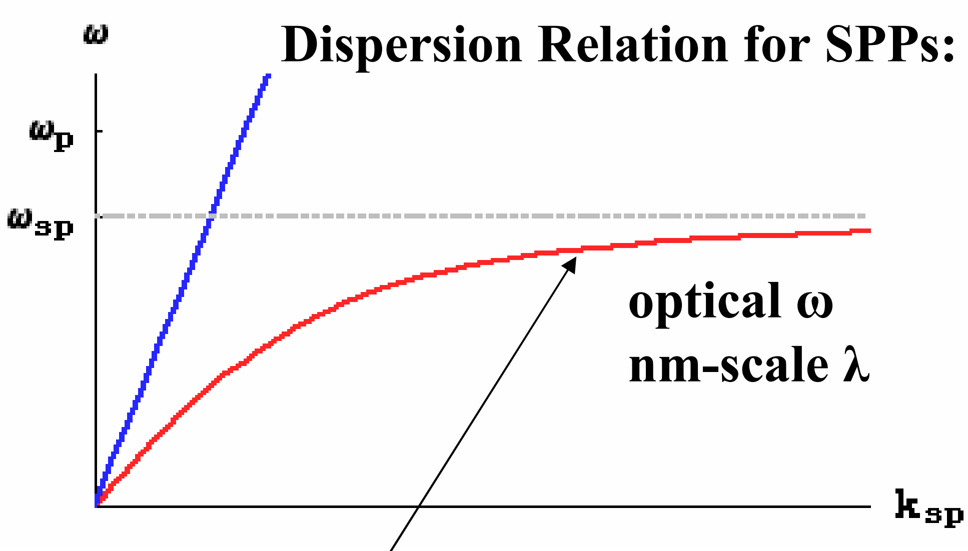
- Note: Solution lies below the light line



Why Plasmonics?



$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}$$



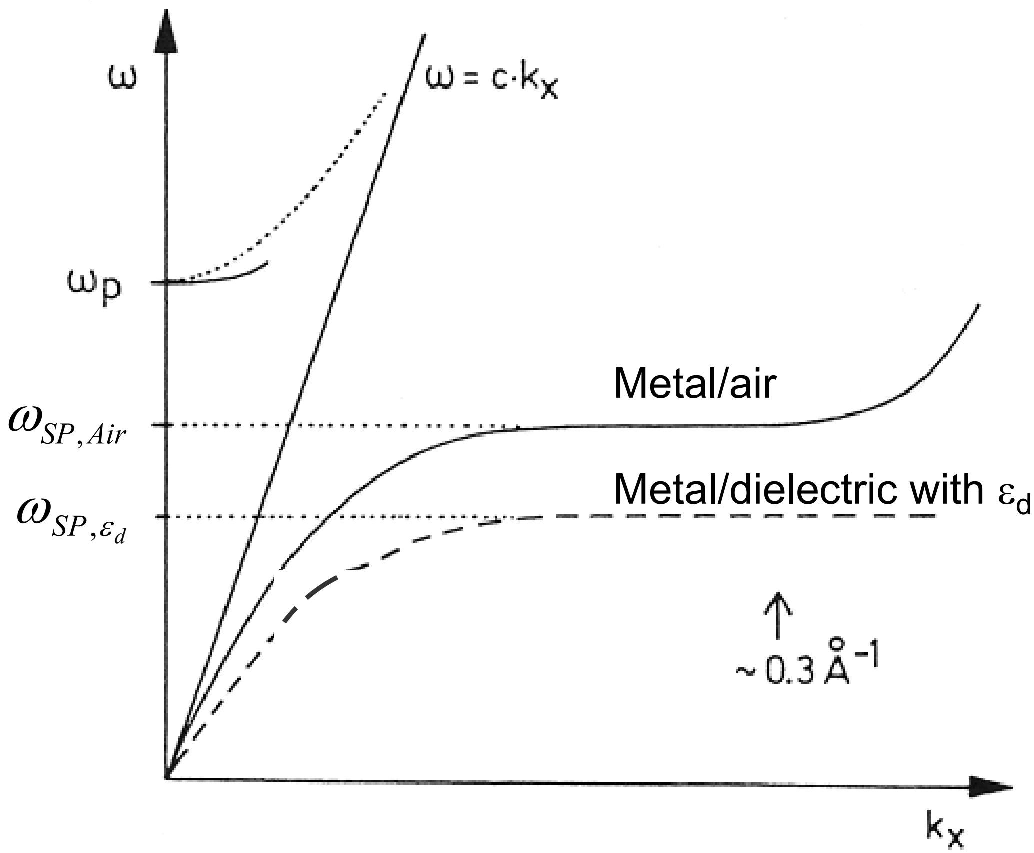
$$\varepsilon_m(\omega) \approx -\varepsilon_d(\omega)$$

$\lambda_p \sim$ very small

SP wavelengths can reach nanoscale at optical frequencies!
SPPs are "x-ray waves" with optical frequencies

Dispersion Relation Surface-Plasmon Polaritons

Dispersion relation plasma modes and SPP



- Note: Higher index medium on metal results in lower ω_{sp}

$\omega = \omega_{sp}$ when: $\varepsilon_m = 1 - \frac{\omega_p^2}{\omega^2} = -\varepsilon_d \Rightarrow \omega^2 - \omega_p^2 = -\varepsilon_d \omega^2 \Rightarrow \omega^2 = \frac{\omega_p^2}{1+\varepsilon_d} \Rightarrow \omega = \frac{\omega_p}{\sqrt{1+\varepsilon_d}}$

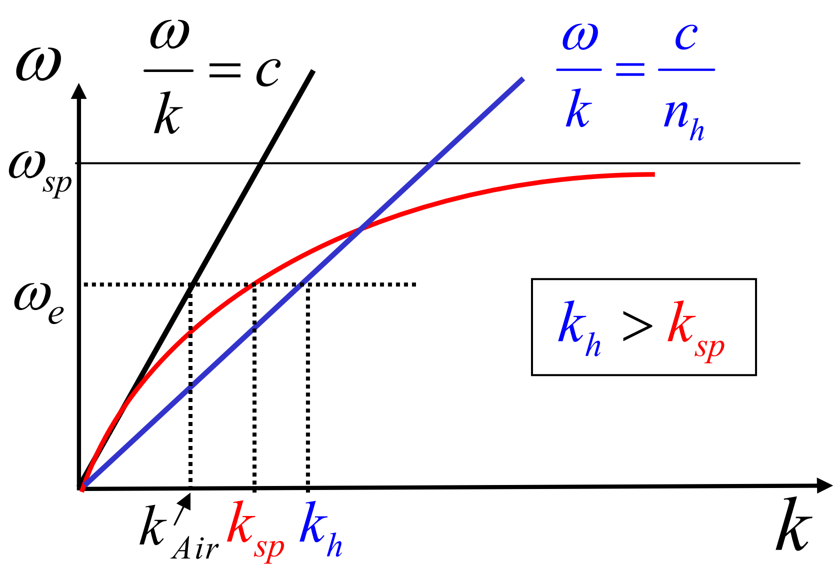
Excitation Surface-Plasmon Polaritons (SPPs) with Light

Problem SPP modes lie below the light line

- No coupling of SPP modes to far field and vice versa (reciprocity theorem)
- Need a "trick" to excite modes below the light line

Trick 1: Excitation from a high index medium

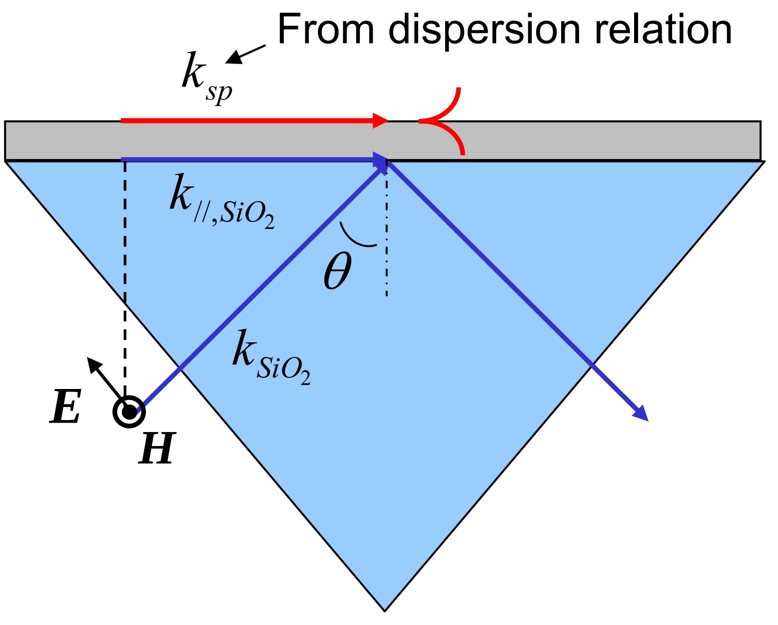
- Excitation SPP at a metal/air interface from a high index medium n = n_h



- SPP at metal/air interface can be excited from a high index medium!
- How does this work in practice ?

Excitation Surface-Plasmon Polaritons with Light

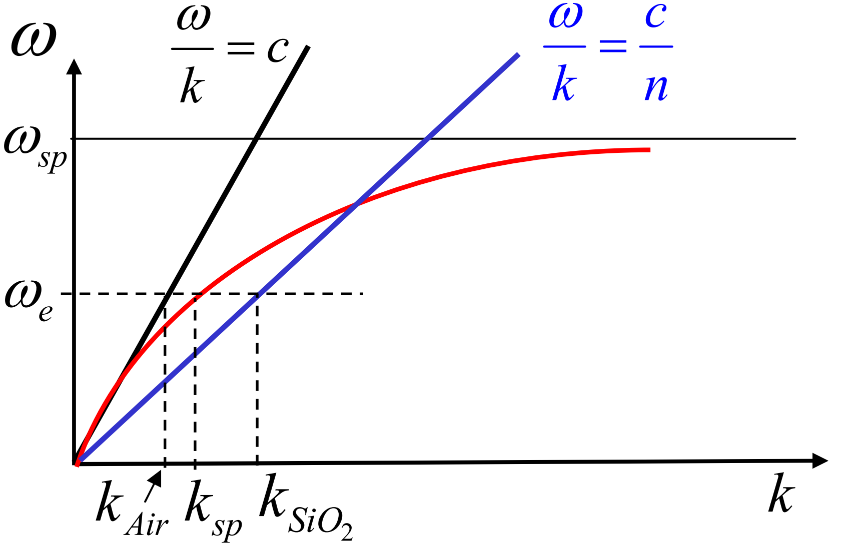
Kretchmann geometry (Trick 1)



- Makes use of SiO_2 prism
- Create evanescent wave by TIR
- Strong coupling when $k_{//,SiO2}$ to k_{sp}

⇓

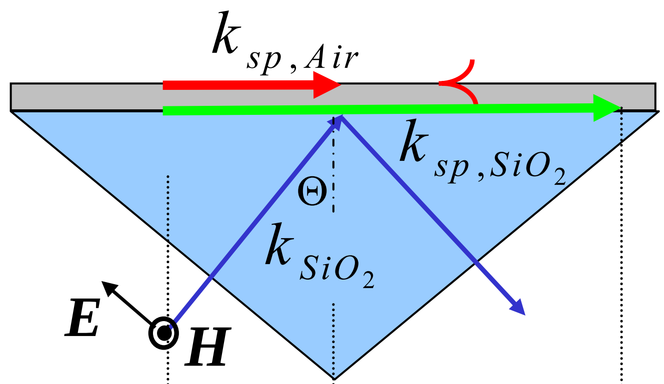
- Reflected wave reduced in intensity



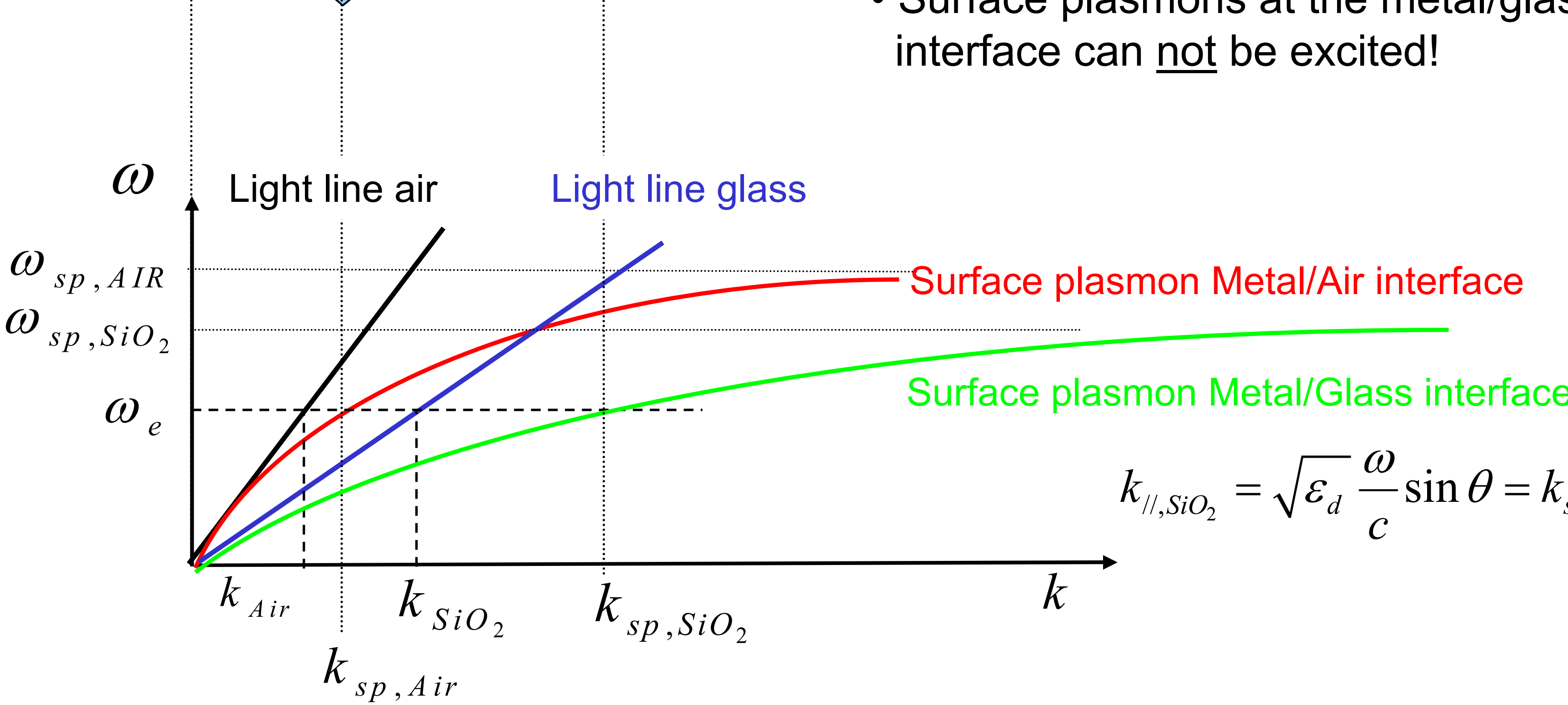
Note: we are matching energy and momentum

Surface-Plasmon is Excited at the Metal/Air Interface

Kretchmann geometry



- Makes use of SiO_2 prism
- Enables excitation surface plasmons at the Air/Metal interface
- Surface plasmons at the metal/glass interface can not be excited!

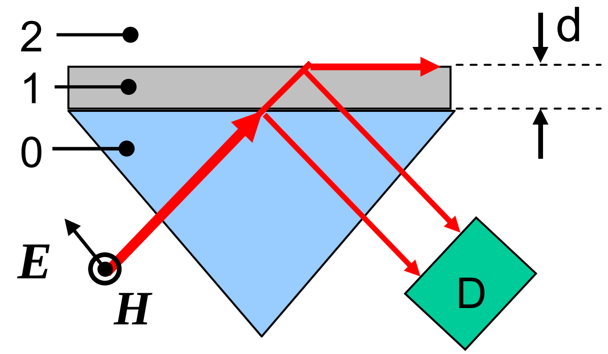


$$k_{//,SiO_2} = \sqrt{\varepsilon_d}\,\frac{\omega}{c}\sin\theta = k_{sp}$$

Quantitative Description of the Coupling to SPP's

Calculation of reflection coefficient

- Solve Maxwell's equations for
- Assume plane polarized light
- Find case of no reflection



- Solution (e.g. transfer matrix theory! ☺)

$$R = \left|\frac{E_r^p}{E_0^p}\right|^2 = \left|\frac{r_{01}^p + r_{12}^p \exp\left(2ik_{z1}d\right)}{1 + r_{01}^p r_{12}^p \exp\left(2ik_{z1}d\right)}\right|^2$$

Plane polarized light

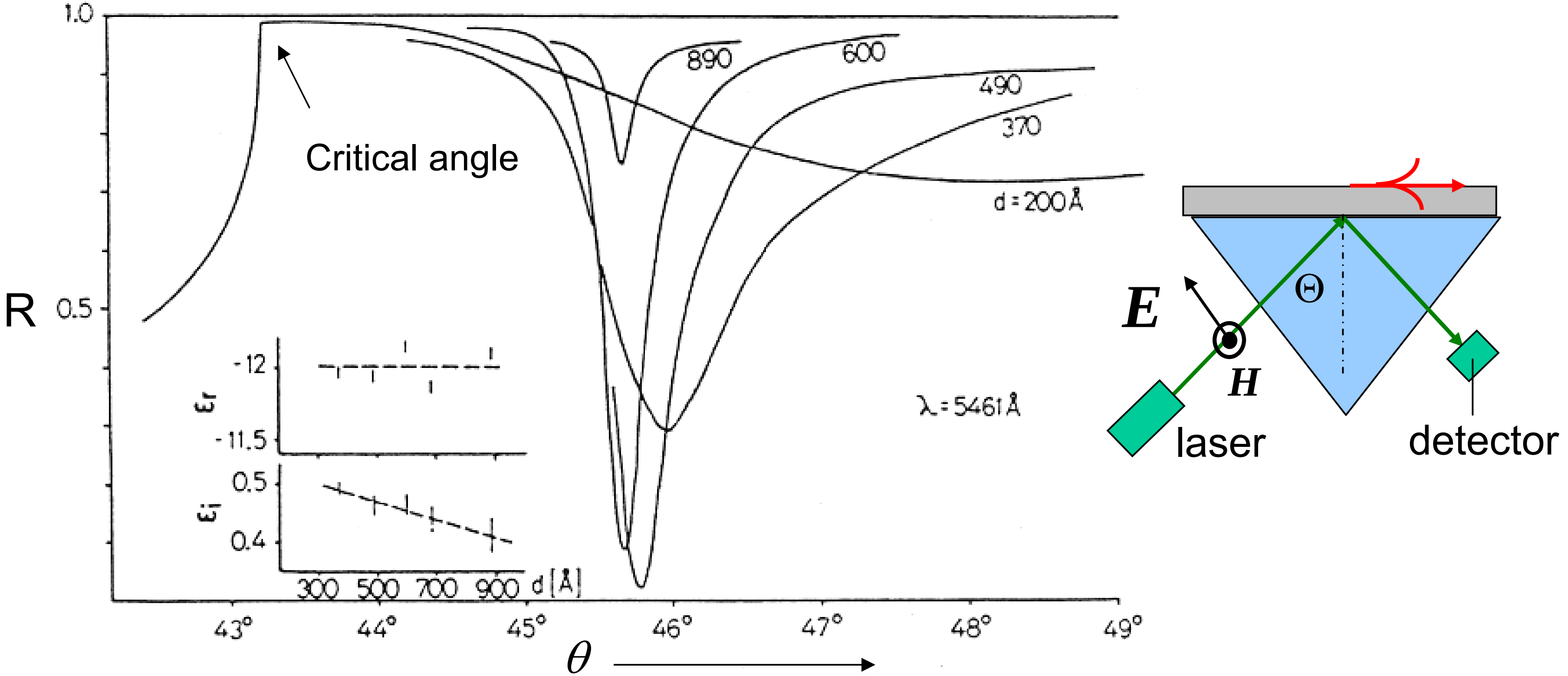
where r_{ik}^p are the amplitude reflection coefficients

$$r_{ik}^p = \left(\frac{k_{zi}}{\varepsilon_i} - \frac{k_{zk}}{\varepsilon_k}\right) \Big/ \left(\frac{k_{zi}}{\varepsilon_i} + \frac{k_{zk}}{\varepsilon_k}\right)$$

Also known as Fresnel coefficients (p 95 optics, by Hecht)

Notes: Light intensity reflected from the back surface depends on the film thickness
There exists a film thickness for perfect coupling (destructive interference between two refl. beams)
When light coupled in perfectly, all the EM energy dissipated in the film)

Dependence on Film Thickness



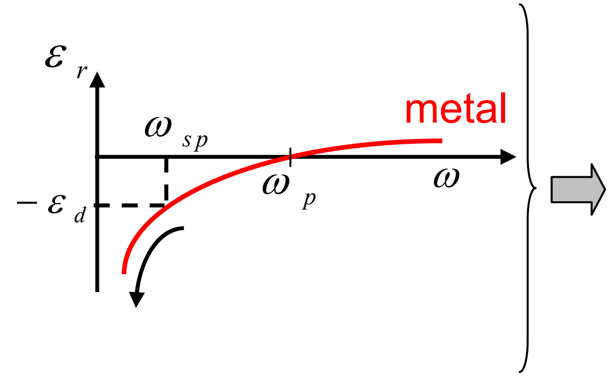
Raether, "Surface plasmons"

- Width resonance related to damping of the SPP
- Light escapes prism below critical angle for total internal reflection
- Technique can be used to determine the thickness of metallic thin films

Quantitative Description of the Coupling to SPP's

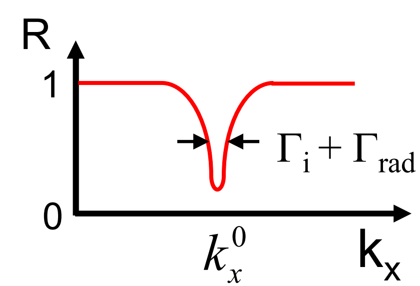
Intuitive picture: A resonating system

- When $|\varepsilon_m'| >> 1$ …well below ω_{sp}:
- and $|\varepsilon_m''| << |\varepsilon_m'|$ …low loss…



Reflection coefficient has Lorentzian line shape (characteristic of resonators)

$$R = 1 - \frac{4\Gamma_i \Gamma_{rad}}{\left[\left(k_x - k_x^0\right)^2 + \left(\Gamma_i + \Gamma_{rad}\right)^2\right]}$$



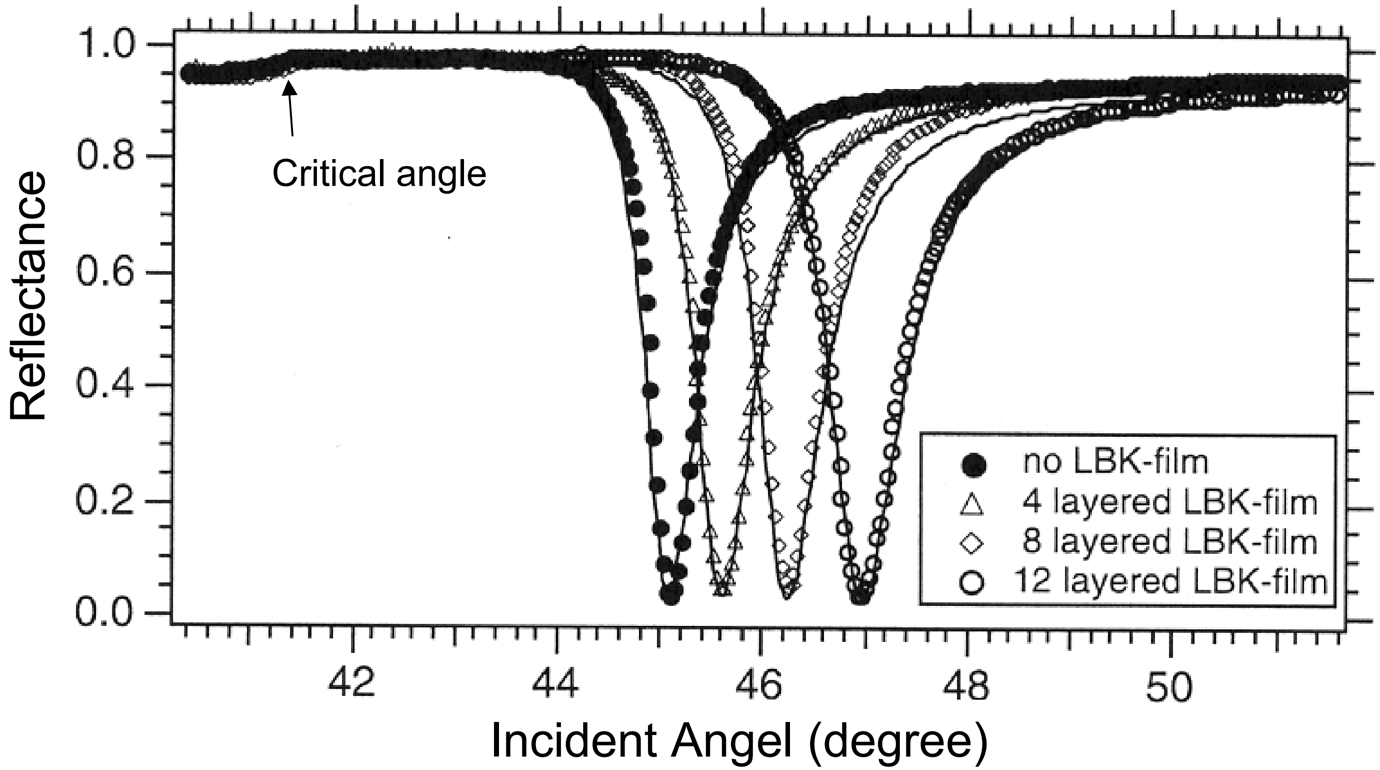
Where Γ_i : Damping due to resistive heating
Γ_{rad}: Damping due to re-radiation into the prism
k_x^0 : The resonance wave vector (maximum coupling)

Note: R goes to zero when $\Gamma_i = \Gamma_{rad}$

Current Use of the Surface Plasmon Resonance Technique

Determination film thickness of deposited films

• Example: Investigation Langmuir-Blodget-Kuhn (LBK) films

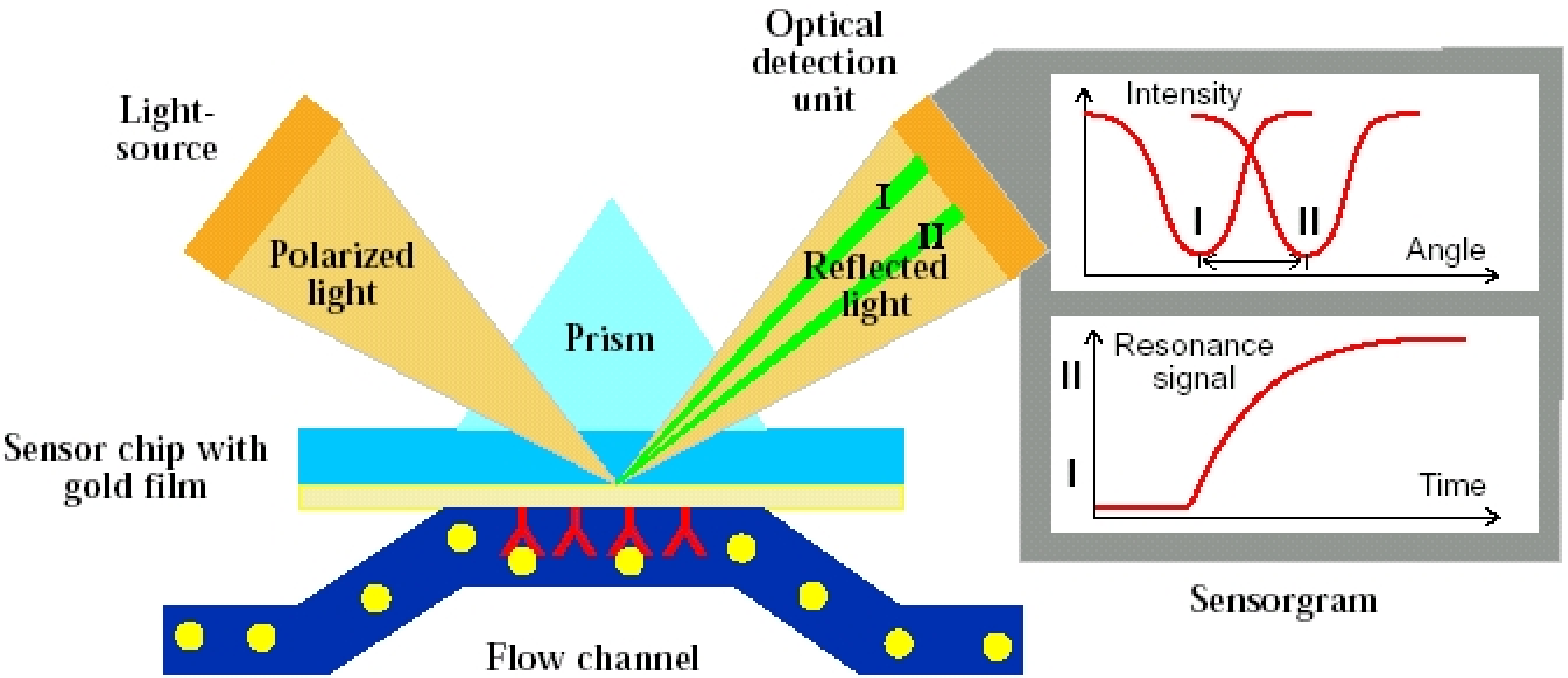


• Coupling angle strongly dependent on the film thickness of the LBK film

• Detection of just a few LBK layers is feasible

Hiroshi Kano, "Near-field optics and Surface plasmon Polaritons", Springer Verlag

Surface Plasmon Sensors

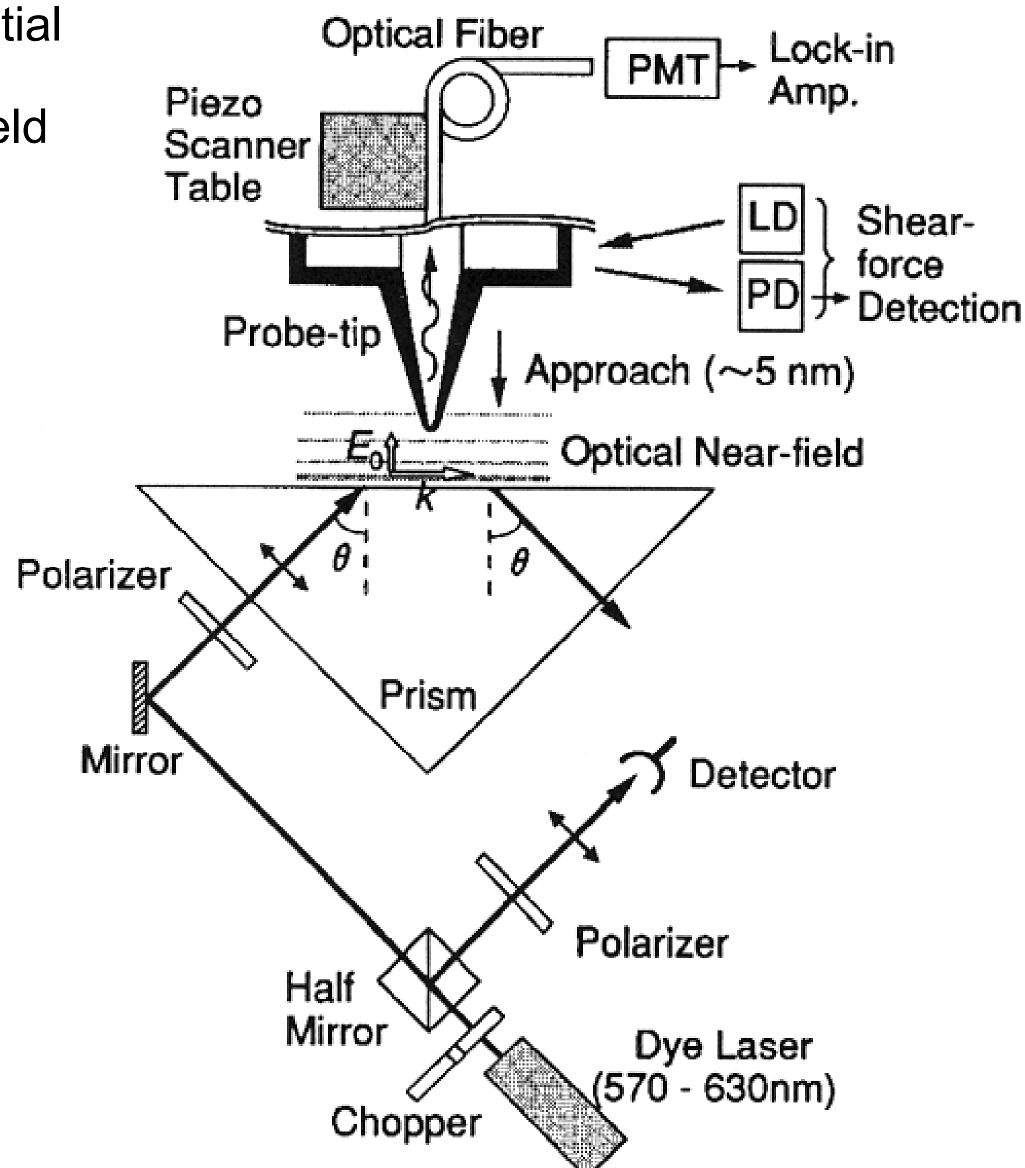


Advantages • Evanescent field interacts with adsorbed molecules only
• Coupling angle strongly depends on ε_d
• Use of well-established surface chemistry for Au (thiol chemistry)

http://chem.ch.huji.ac.il/~eugeniik/spr.htm#reviews

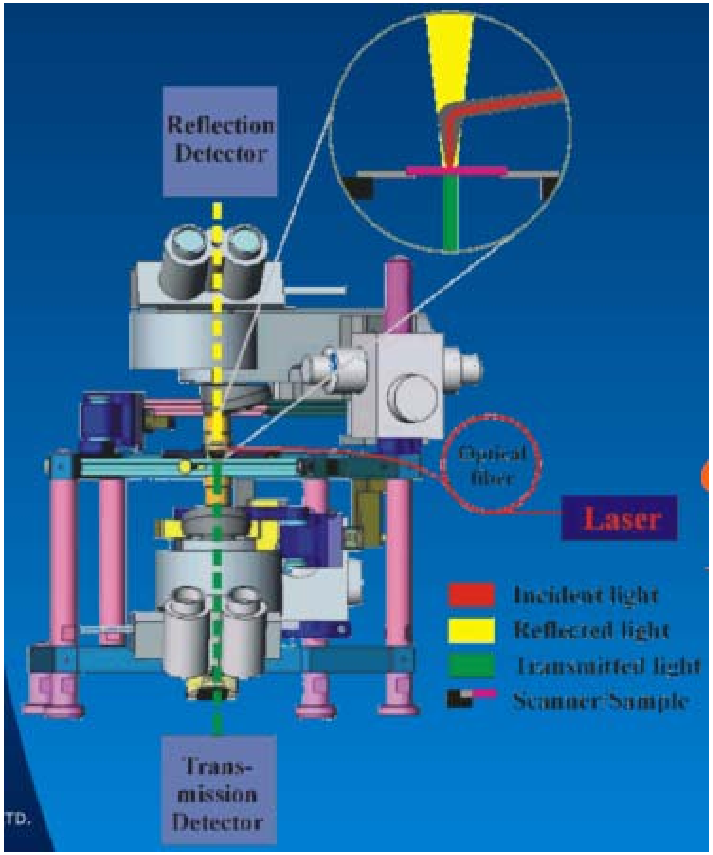
Imaging SPP waves

- Near-field optics is essential
- Tip "taps" into the near-field



Purdue Near-Field Optical Microscope

- Nanonics MultiView 2000
- NSOM / AFM
- Tuning Fork Feedback Control
  - Normal or Shear Force
- Aperture tips down to 50 nm
- AFM tips down to 30 nm
- Radiation Source
  - 532 nm

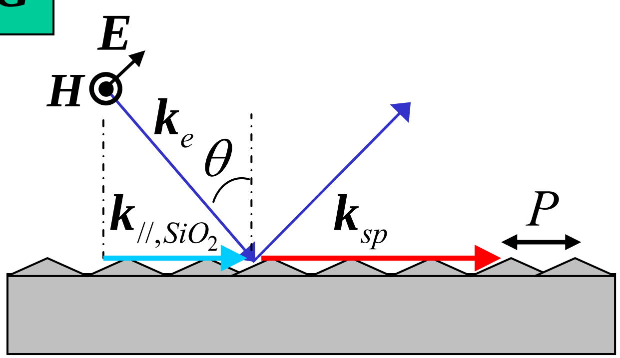


Picture taken from Nanonics

Excitation Surface-Plasmon Polaritons with Gratings (trick 2)

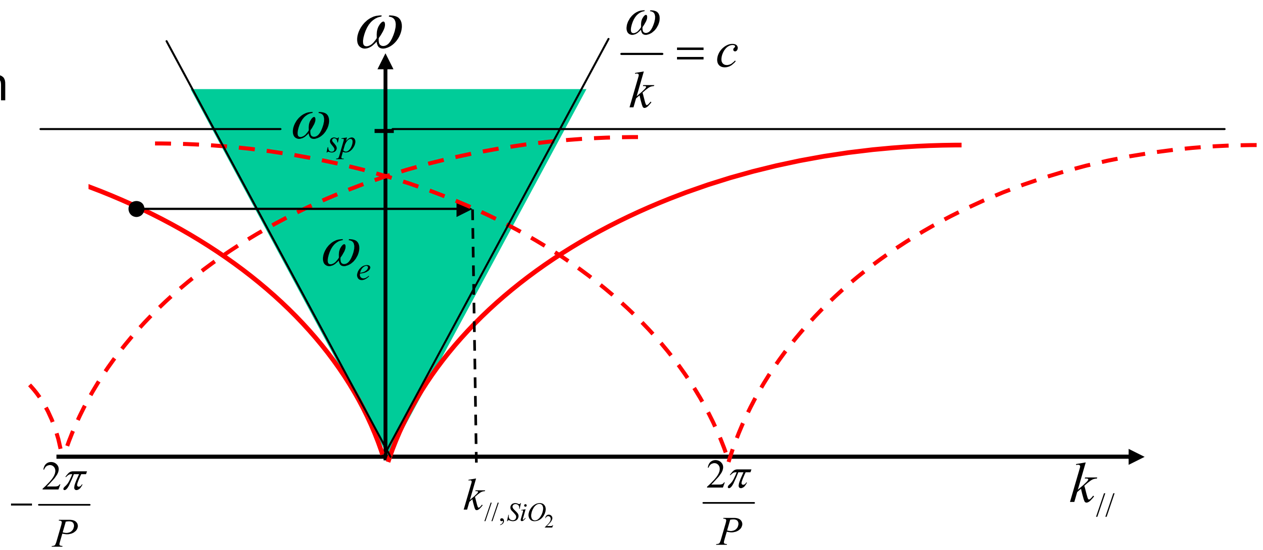
Grating coupling geometry (trick 2)

- Bloch: Periodic dielectric constant couples waves for which the k-vectors differ by a reciprocal lattice vector $\boldsymbol{G}$
- Strong coupling occurs when $\boldsymbol{k}_{//,SiO_2} = \boldsymbol{k}_{sp} \pm m\boldsymbol{G}$

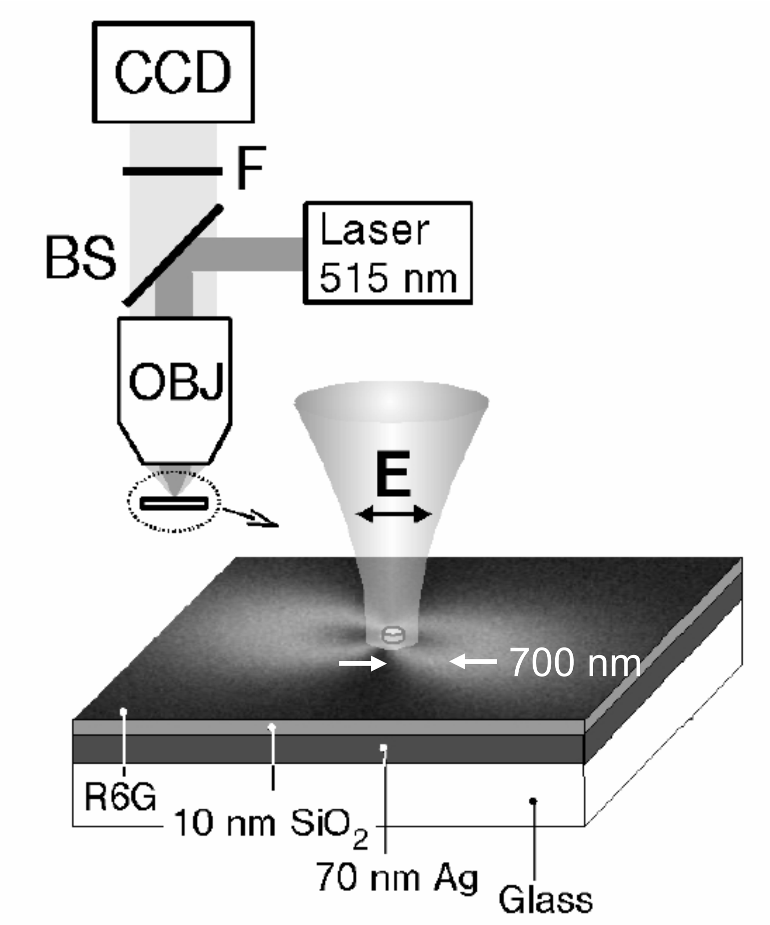


where:
$$\begin{cases} k_{//,SiO_2} = \left|\boldsymbol{k}_e\right| = \sqrt{\varepsilon_d}\,\dfrac{\omega}{c}\sin\theta \\ k_{sp} = \dfrac{\omega}{c}\left(\dfrac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2} \\ \left|\boldsymbol{G}\right| = 2\pi/P \end{cases}$$

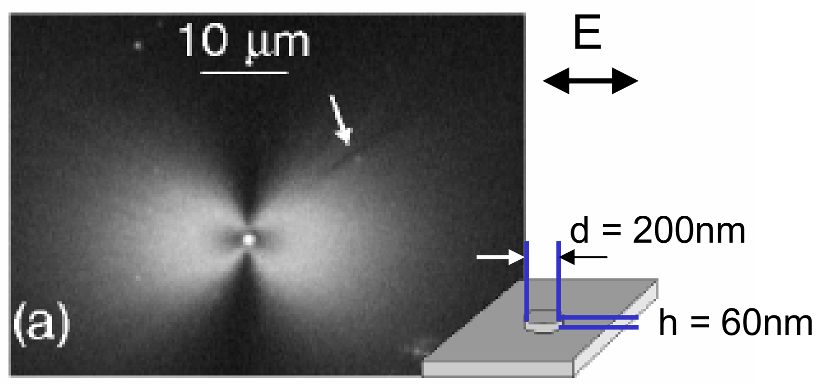
- Graphic representation

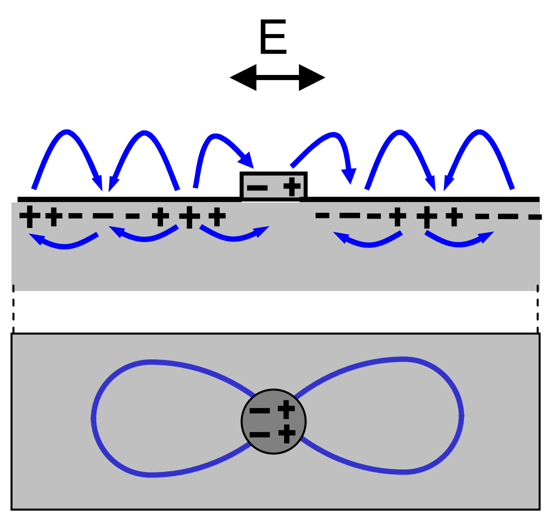


Excitation Surface-Plasmon Polaritons with Dots (Trick 3)



Dipolar radiation pattern





- Strong coupling: $k_{//,SiO_2} = k_{sp} \pm \Delta k_{dot}$

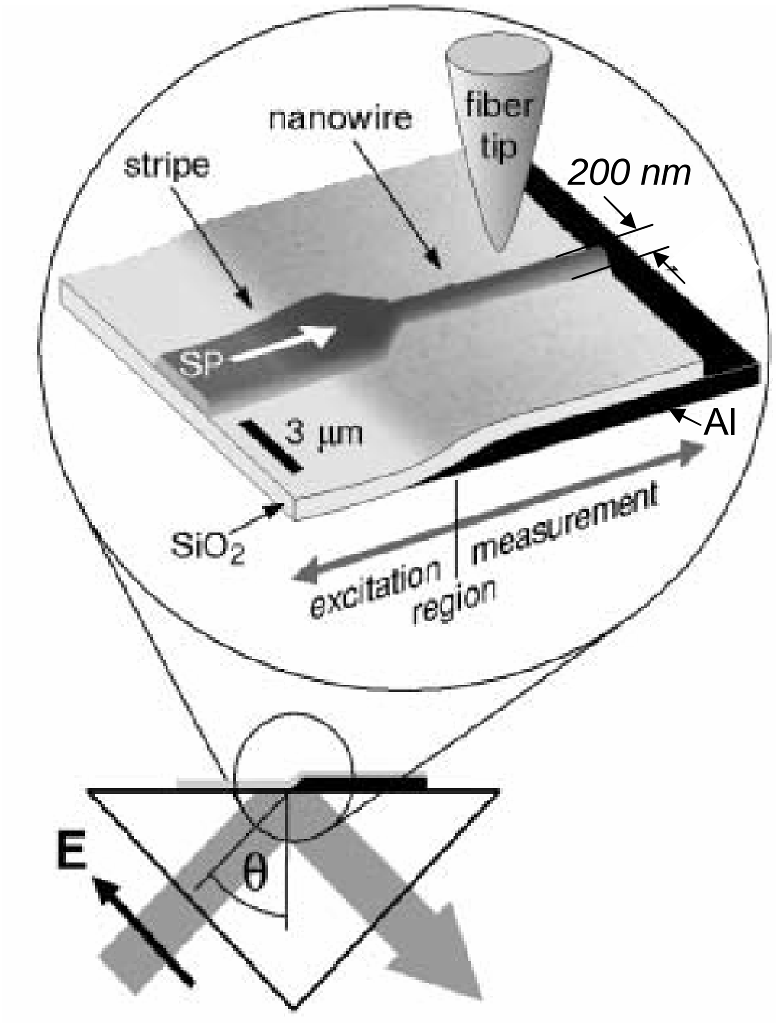
Spatial Fourier transform of the dot contains significant contributions of Δk_{dot} values upto 2π/d

H. Ditlbacher, Appl. Phys. Lett. ***80****, 404 (2002)*

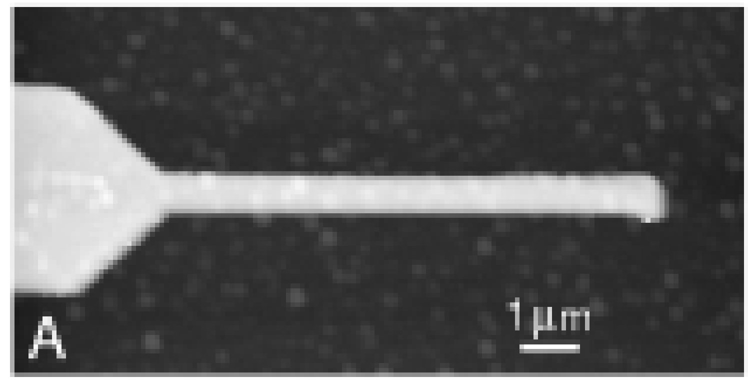
- Dipole radiation in direction of charge oscillation!
- Reason: Plasmon wave is longitudinal

Excitation SPPs on stripes with d < λ

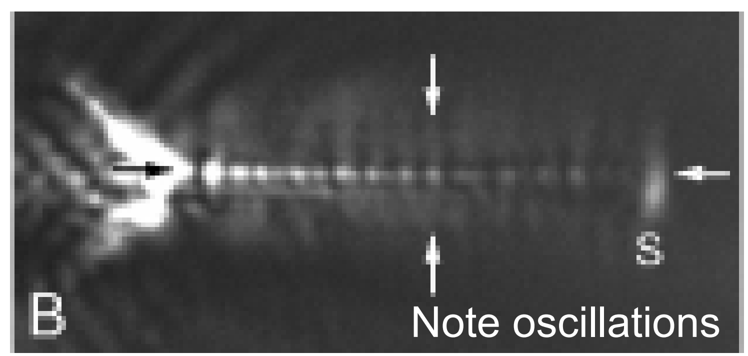
Excitation using a launch pad



Atomic Force Microscopy image



Near Field Optical Microscopy image



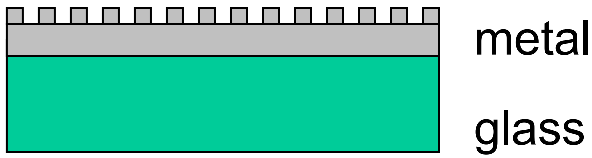
End stripe

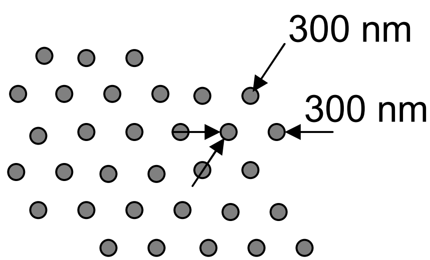
J.R. Krenn et al., Europhys.Lett. ***60, 663-669*** *(2002)*

2D Metallo-dielectric Photonic Crystals

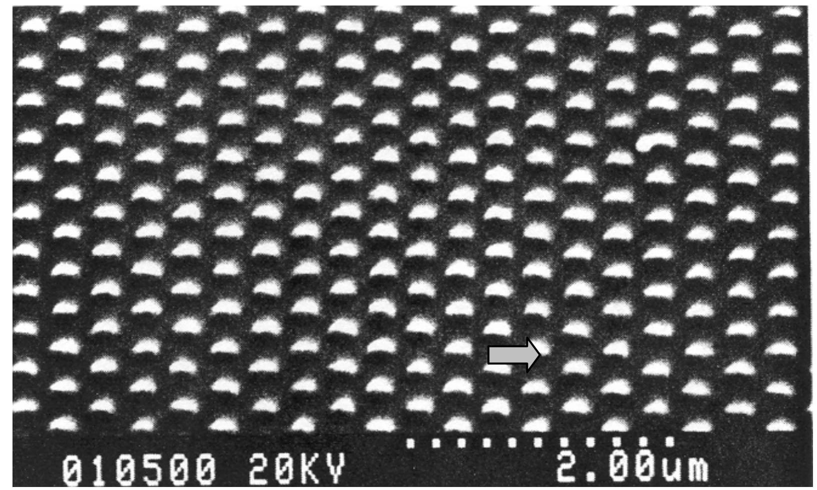
Full photonic bandgap for SPPs

- Hexagonal array of metallic dots





Scanning Electron Microscopy image (tilted)

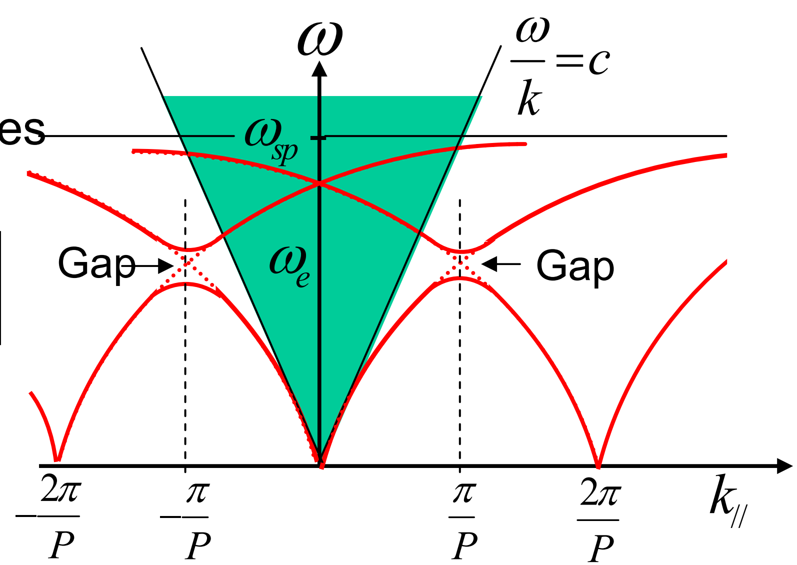


S.C. Kitson, Phys Rev Lett. ***77****, 2670 (1996)*

- Array causes coupling between waves for which:

$k_{sp} = \pi/P$ or $\lambda_{sp}=2\pi/k_{sp}= 2P$

- Gap opens up at the zone boundary

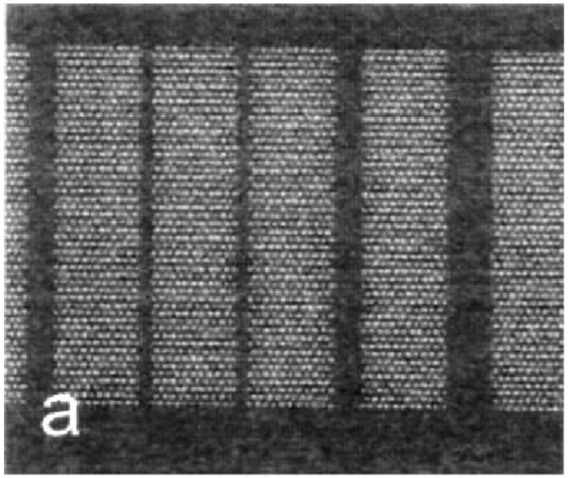


Guiding SPPs in 2D metallo-dielectric Photonic Crystals

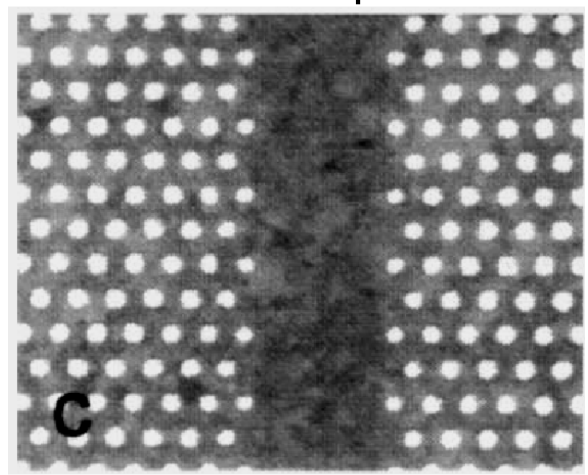
Guiding along line defects in hexagonal arrays of metallic dots (period 400 nm)

- Scanning electron microscopy images

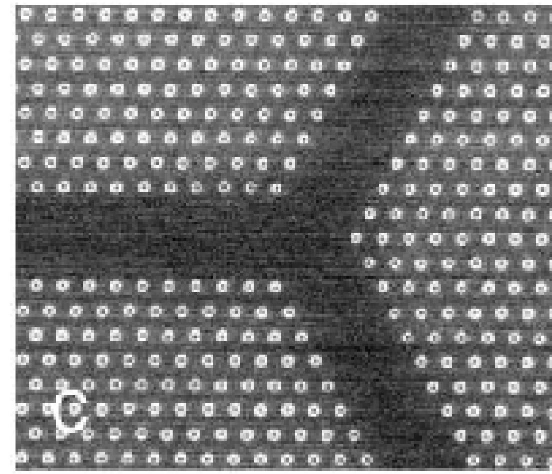
Linear guides



Close-up



Y-Splitter



- SPP is confined to the plane
- Full photonic bandgap confines SPP to the line defect created in the array

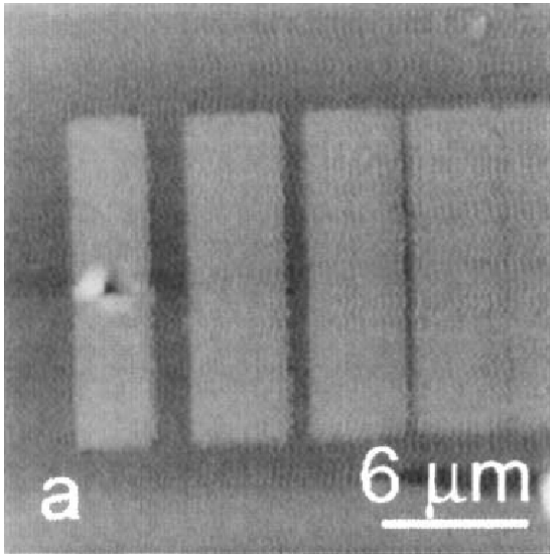
S.I. Bozhevolnyi, Phys Rev Lett. ***86****, 3008 (2001)*

Guiding SPPs in 2D metallo-dielectric Photonic Crystals

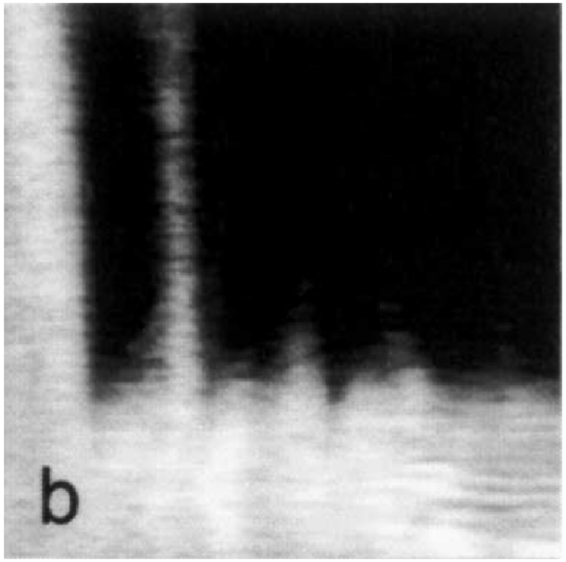
First results

- Scanning electron microscopy images

Atomic Force Microscopy image



Near-field Optical Microscopy image



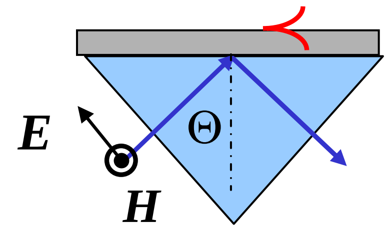
Dot spacing: d = 380 nm
Excitation: λ_e = 725 nm
SPP: λ_{sp} = 760 nm = 2d

S.I. Bozhevolnyi, Phys Rev Lett. ***86****, 3008 (2001)*

Intermediate Summary

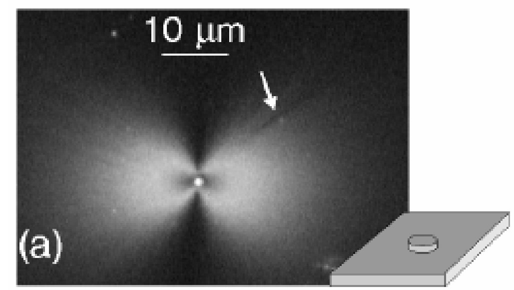
Coupling light to surface plasmon-polaritons

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



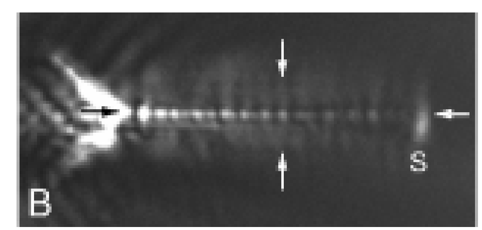
- Grating coupling $\mathbf{k}_{//,Air} = \mathbf{k}_{sp} \pm m\mathbf{G}$

- Coupling using a metal dot (sub-λ structure)

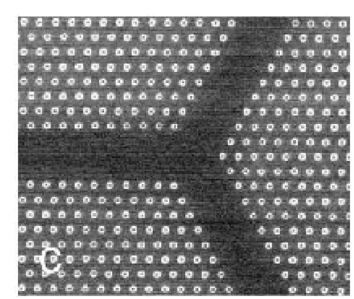


Guiding geometries

- Stripes and wires



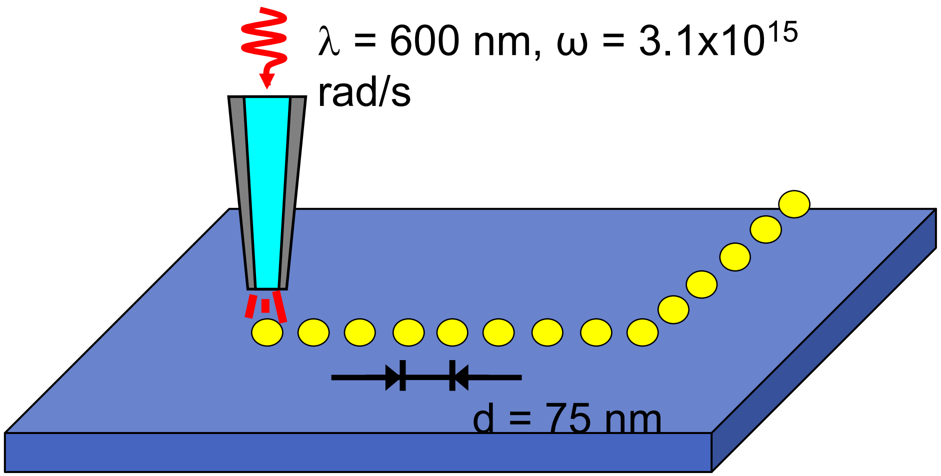
- Line defects in hexagonal arrays (2d photonic crystals)



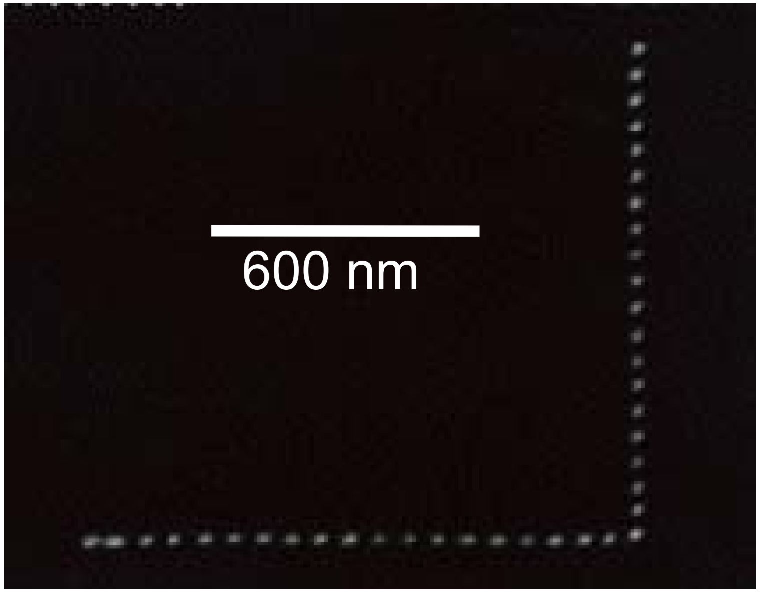
- Next lecture: nanoparticle arrays

Guiding of light along an array of Au nanoparticles ?

- Near field optical excitation



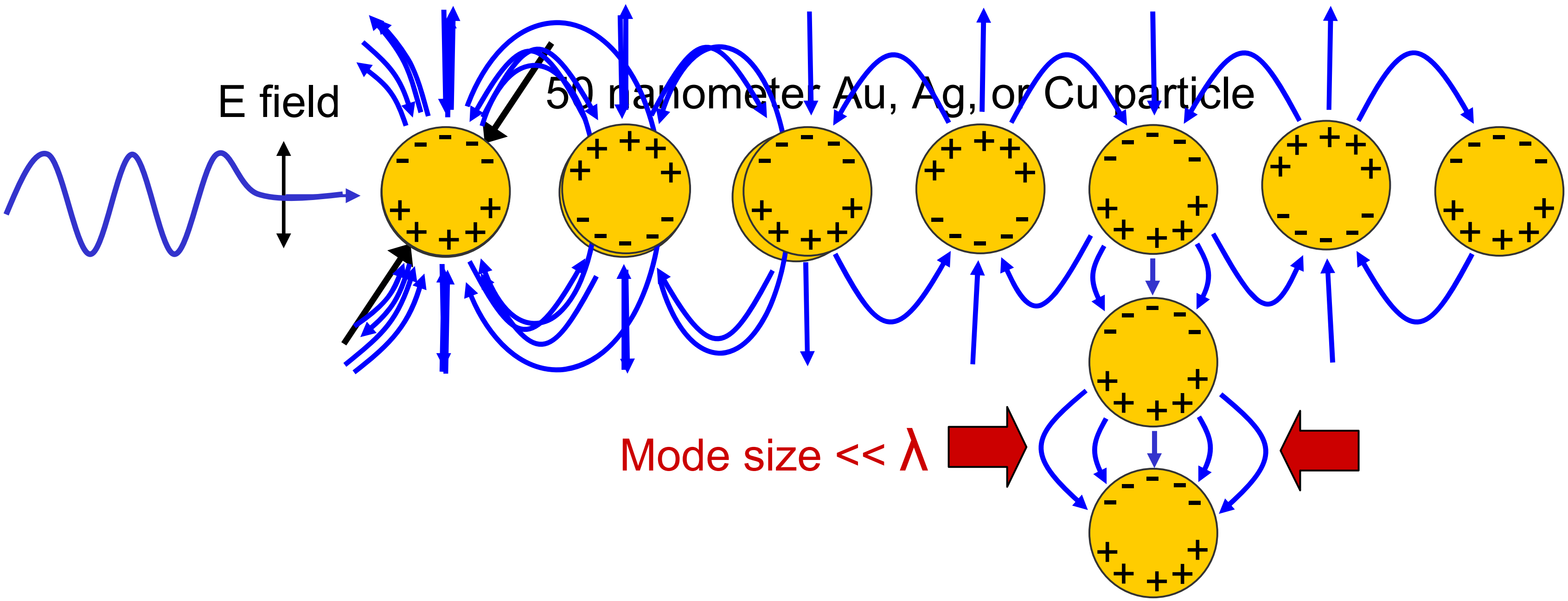
- SEM of array of 50 nm Au particles



- 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

EM Near-field Interaction between Nanoparticles



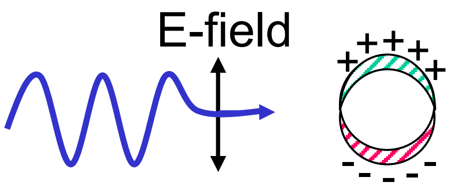
- Light can penetrate metallic nanoparticles and set the electrons in motion
- This collective electron motion is called a plasmon
- Plasmonics: Guiding "light" along metallic nanostructures
- Loss per unit length ≈ 3 dB/μm …. Loss per device may be manageable

Excitation of a Single Metal Nanoparticle

Particle

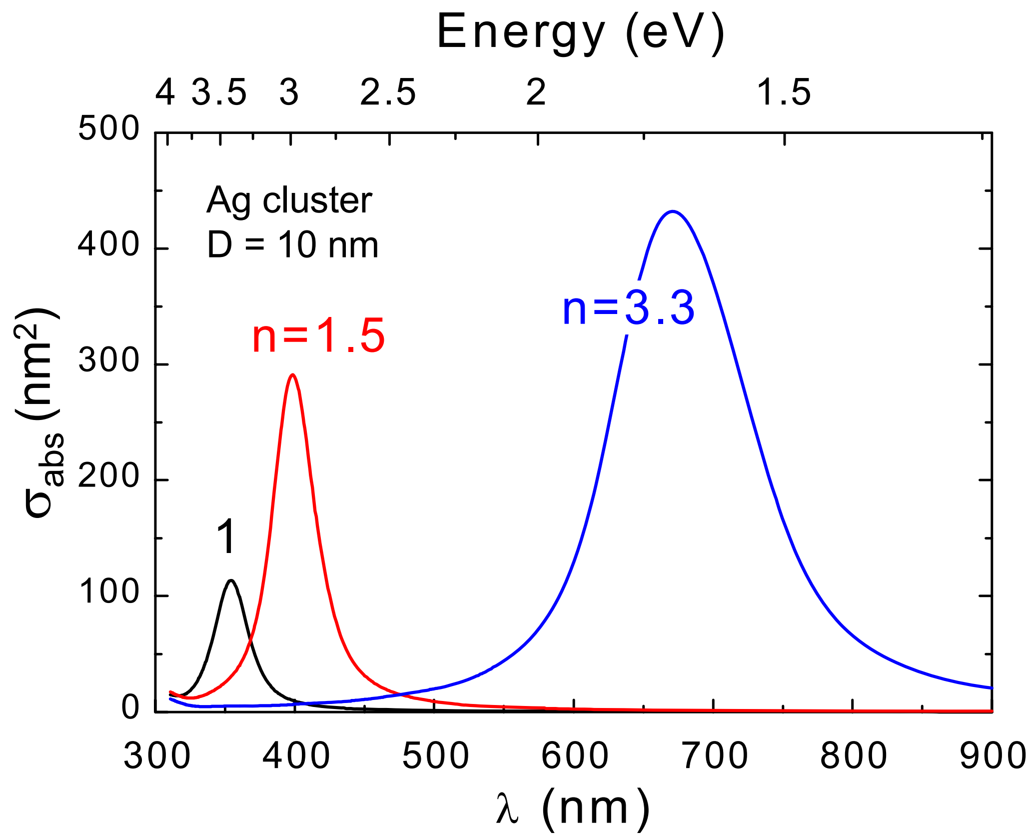
Volume = V_0

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



Host matrix

$\varepsilon_H = \varepsilon_{1,H} = n_H^2$



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

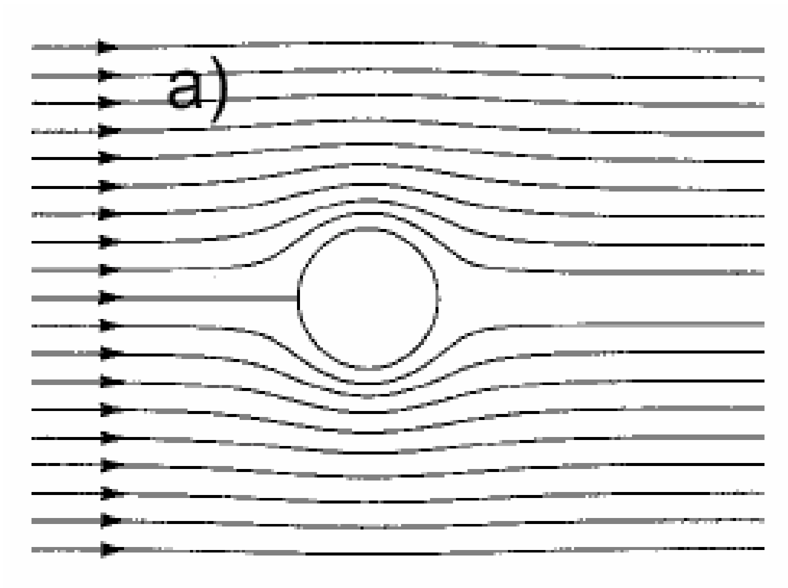
G. Mie Ann. Phys. 25, 377 (1908)

Origin Enhanced Absorption Cross-section

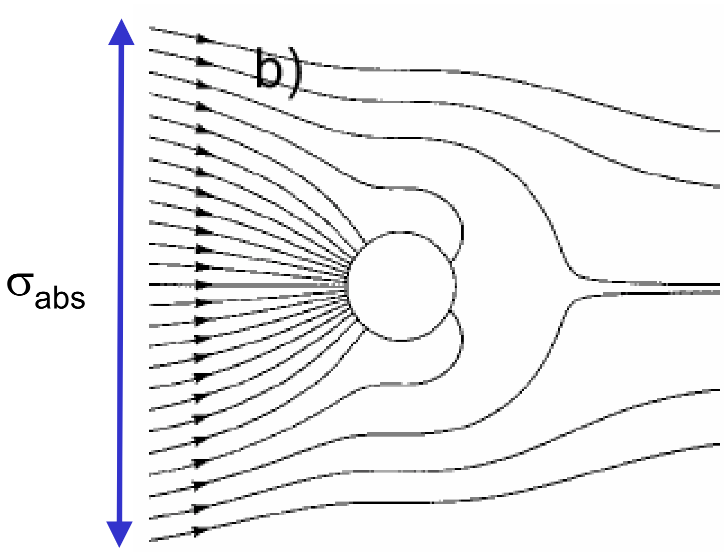
Poynting vector

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

Off resonance

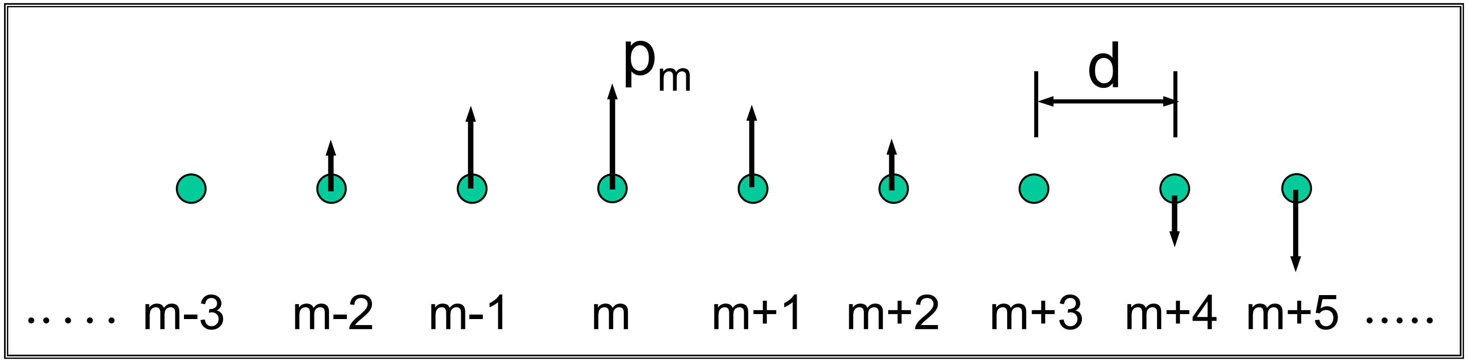


On resonance



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:

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

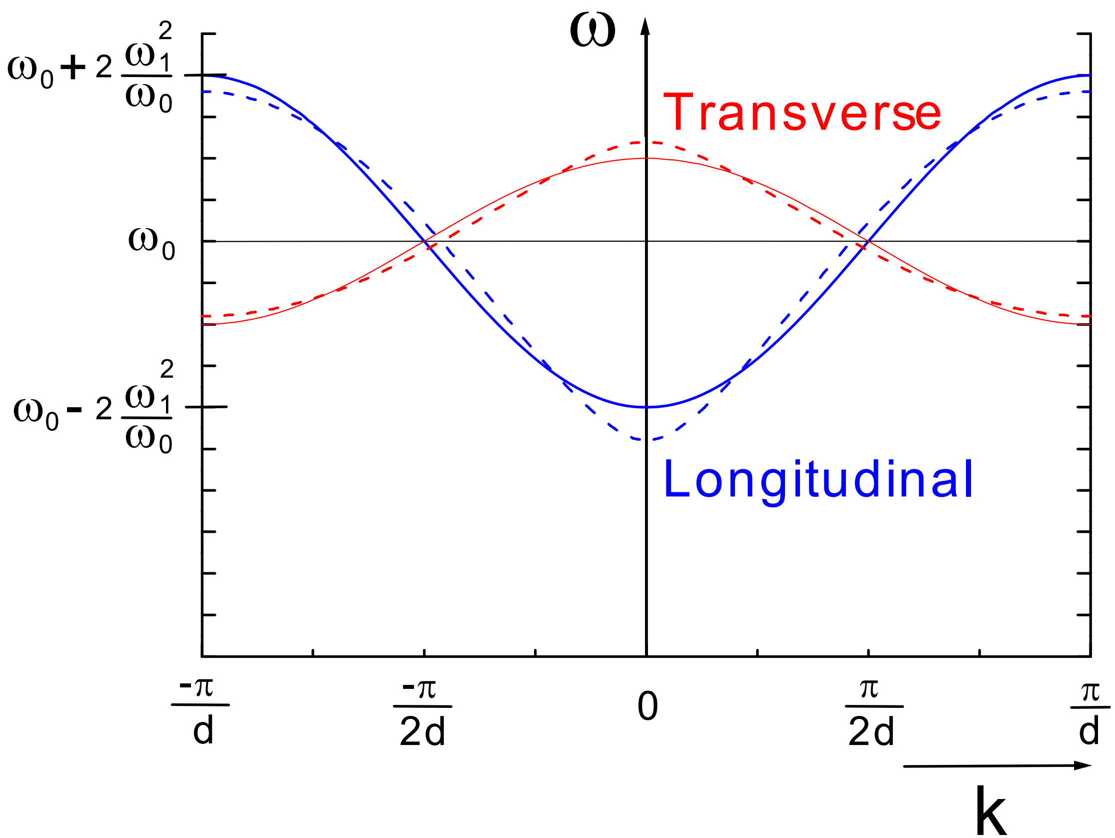
Where $$\omega_1^2 = \frac{\rho V e}{4\pi\varepsilon_0 m_e n^2 d^3}$$

$\gamma \equiv$ a polarization dependent constant:

- $\gamma_T = 1$: ↑ $p_{T,m}$ ↑ $p_{T,m+1}$
- $\gamma_L = -2$: → $p_{L,m}$ → $p_{L,m+1}$

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

Dispersion Relation for Plasmon Modes



$$\omega = \omega_0 + \gamma_i \frac{\omega_1^2}{\omega_0}\cos(kd)$$

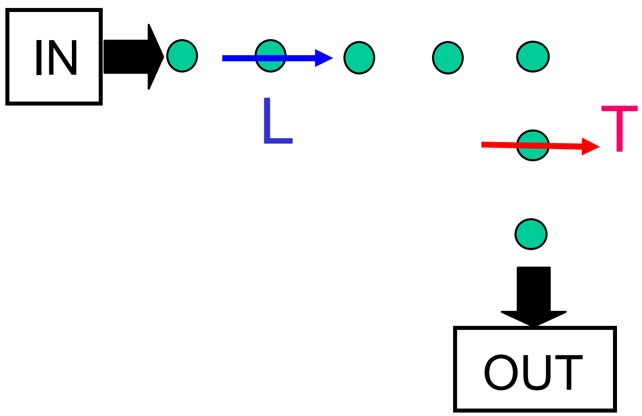
Where $\omega_1^2 = \dfrac{\rho V e}{4\pi\varepsilon_0 m_e n^2 d^3}$

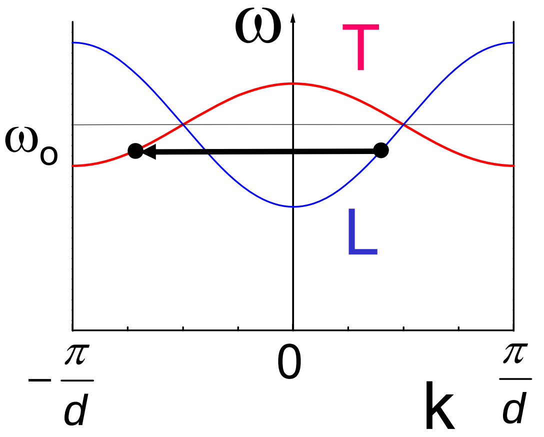
$$v_{g,i} = \frac{d\omega}{dk} = -\gamma_i \frac{\omega_1^2}{\omega_0} d\sin(kd)$$

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



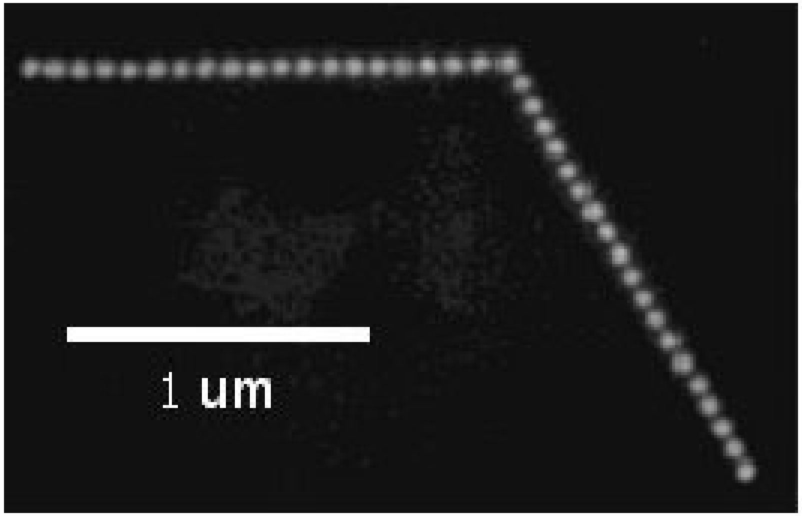


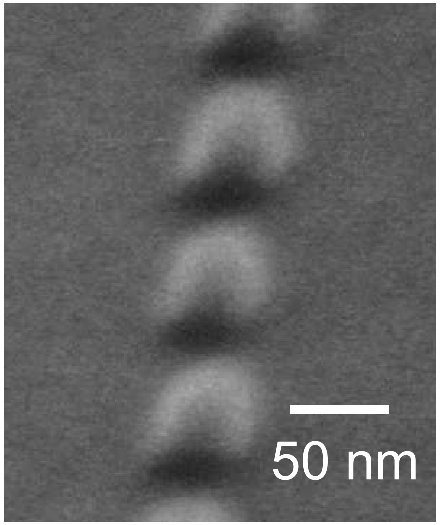
Calculation of power transmission coefficient, η_T (ω, pol):

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

Maximum η_T at ω_0

SEM Images of Nanoparticle Arrays



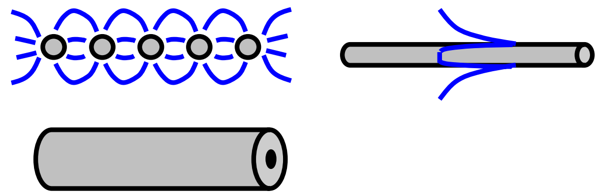


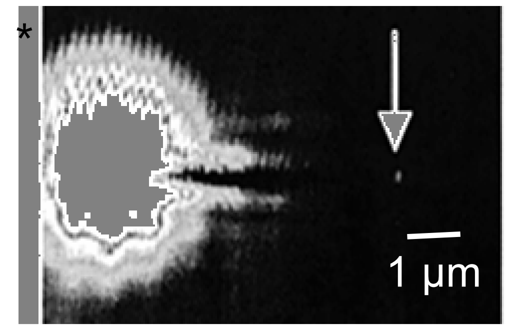
- Array of 50 nm diameter Au dots spaced by 75 nm
- Good control over particle size, shape, interparticle spacing

The Future of Metal Optics

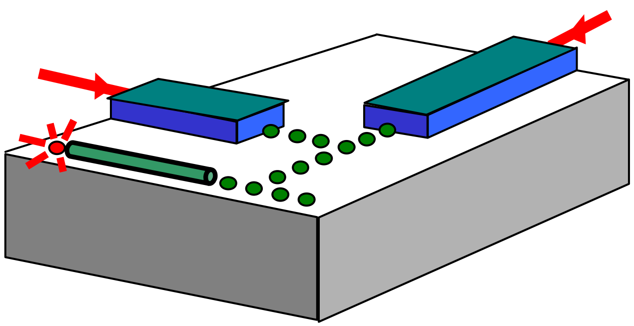
Photonics

• Basic building blocks





• More complex architectures



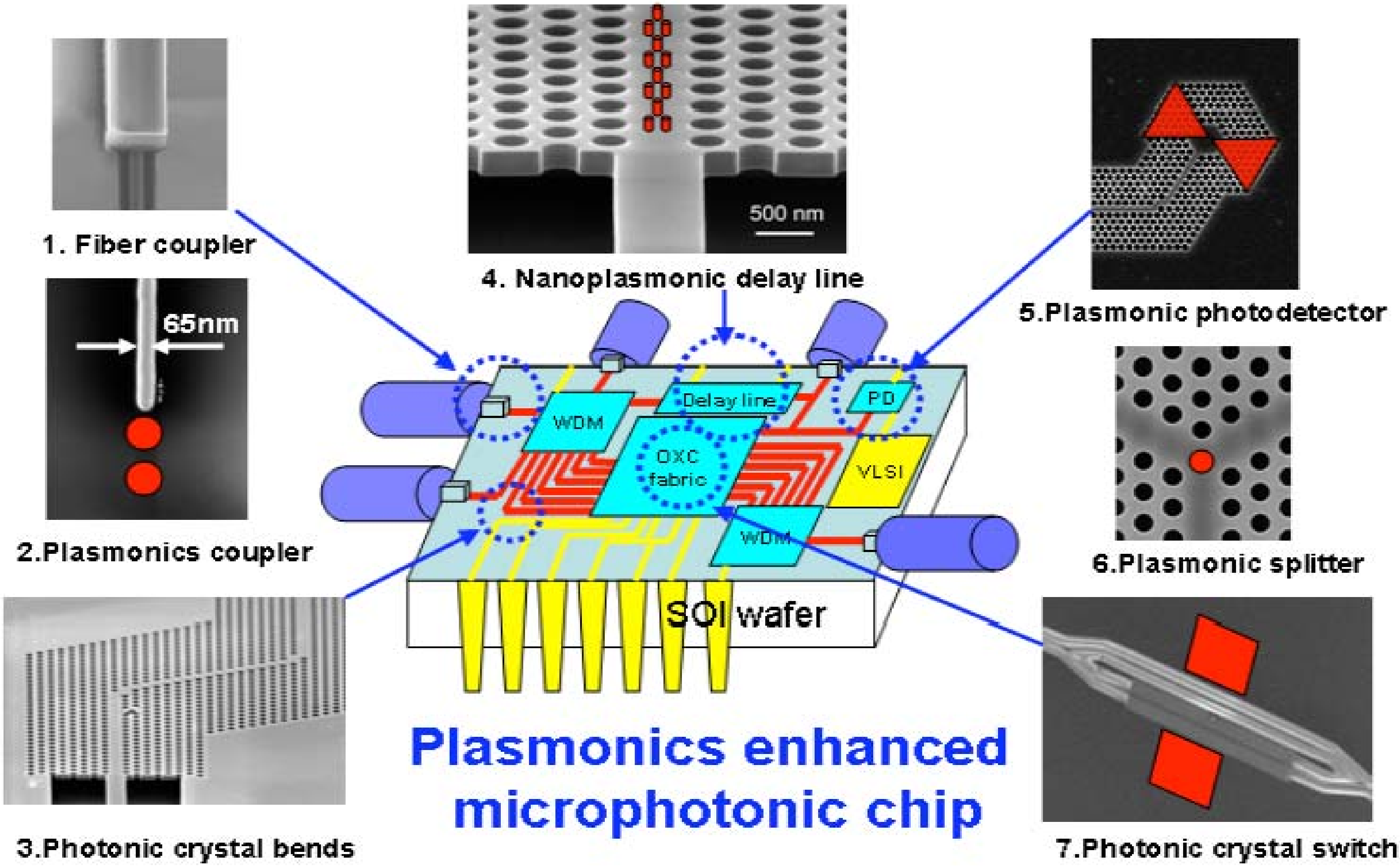
• Applications in biology for “Optical microscopy” ?

• Applications in high-density optical data storage ?

• Fundamental studies of light-matter interaction

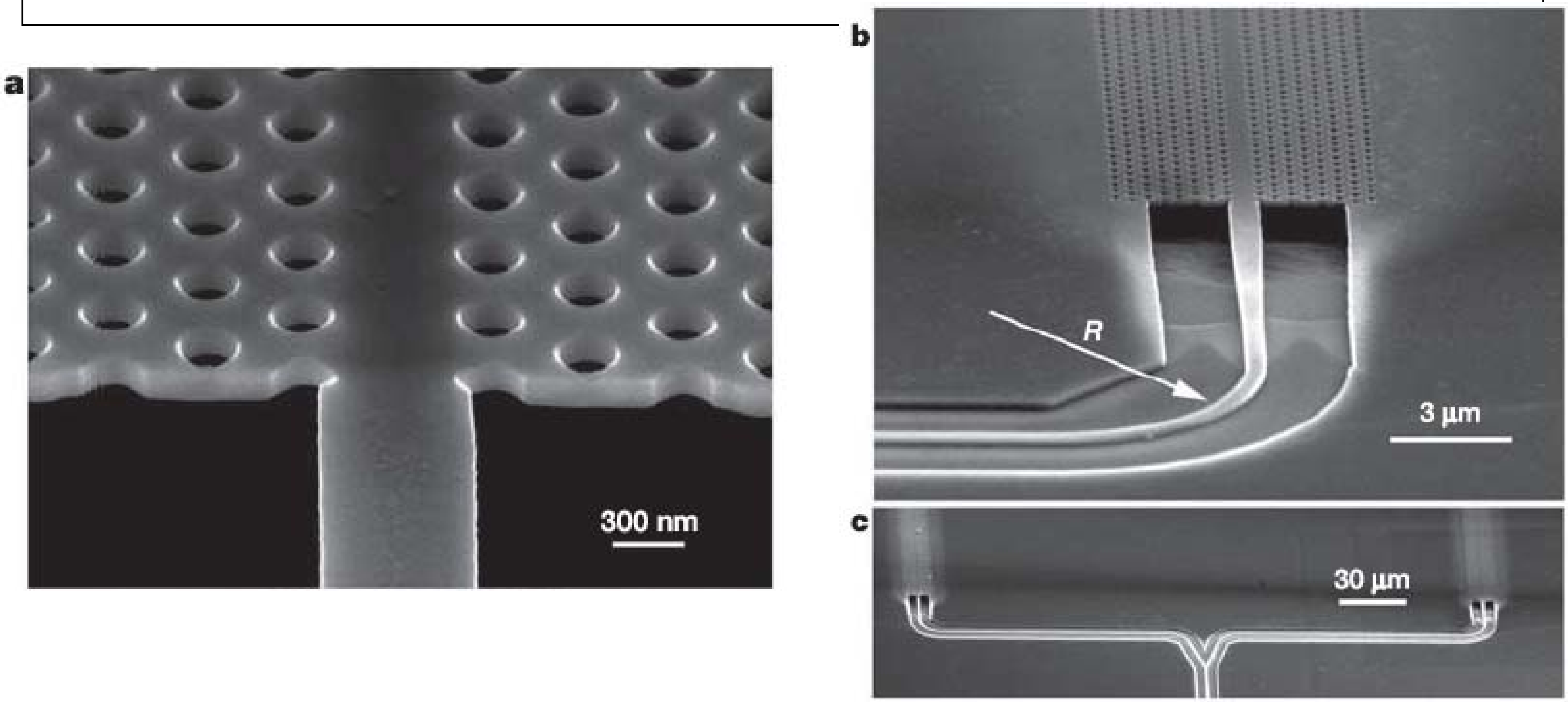
** R.M. Dickson et al., J. Phys. Chem. B **104**, 6095-6098 (2000)*

Conceptual Si photonic chip



Y. A. Vlasov, IBM

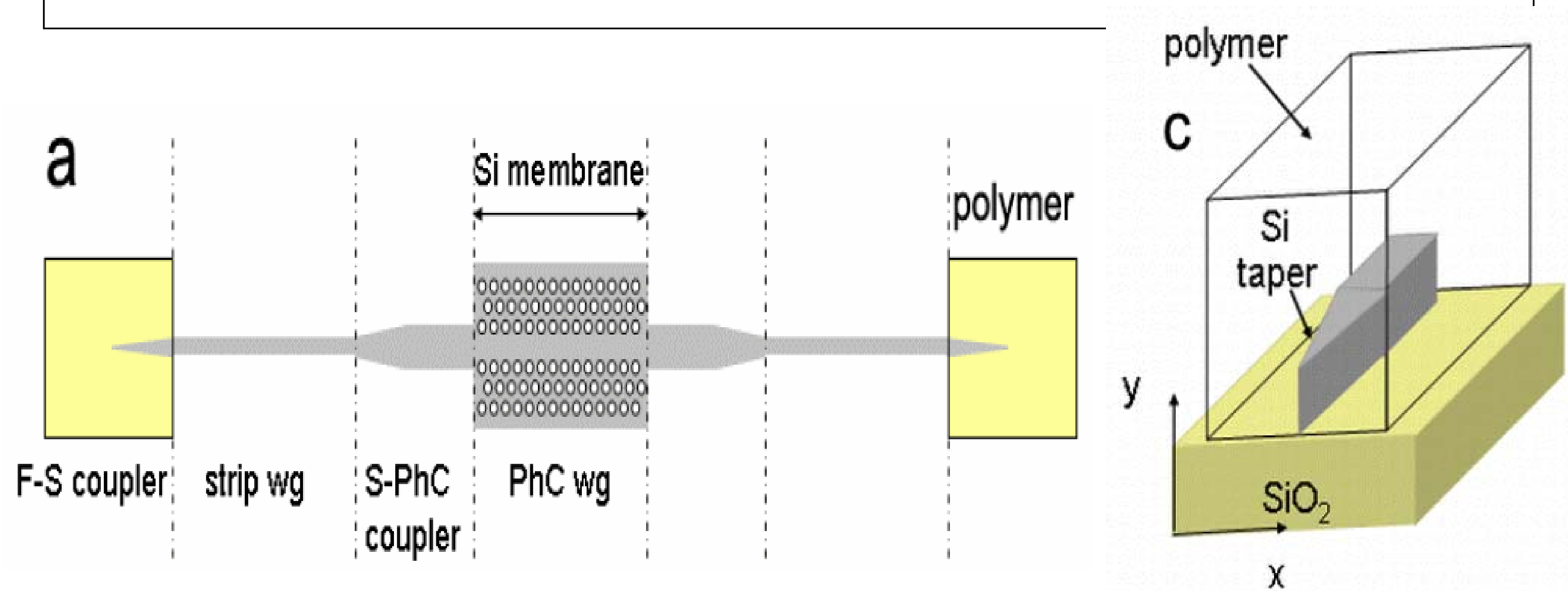
Si photonic crystal switch



Y. A. Vlasov, et al, *Nature*, 2005

- **PC based Mach-Zehnder interferometer**

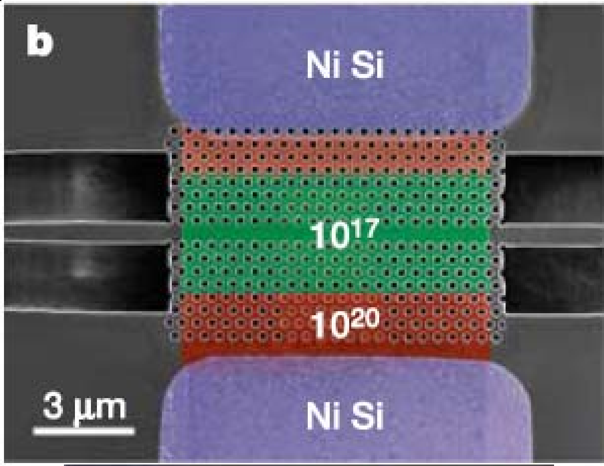
Fiber to Si-PC coupling

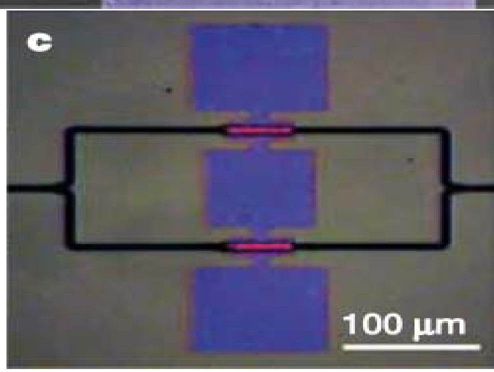


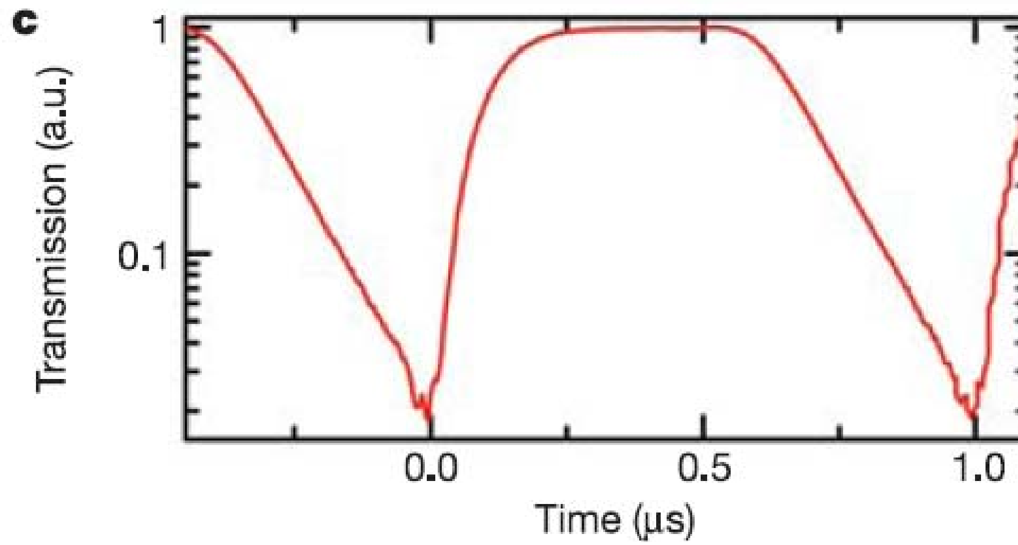
Y. A. Vlasov, et al, *Opt. Express*, 2003

- **There can be 30dB loss due to geometrical mismatch**
- **Specialized fiber to Si coupling using polymer based coupler**

Si-PC switch operation



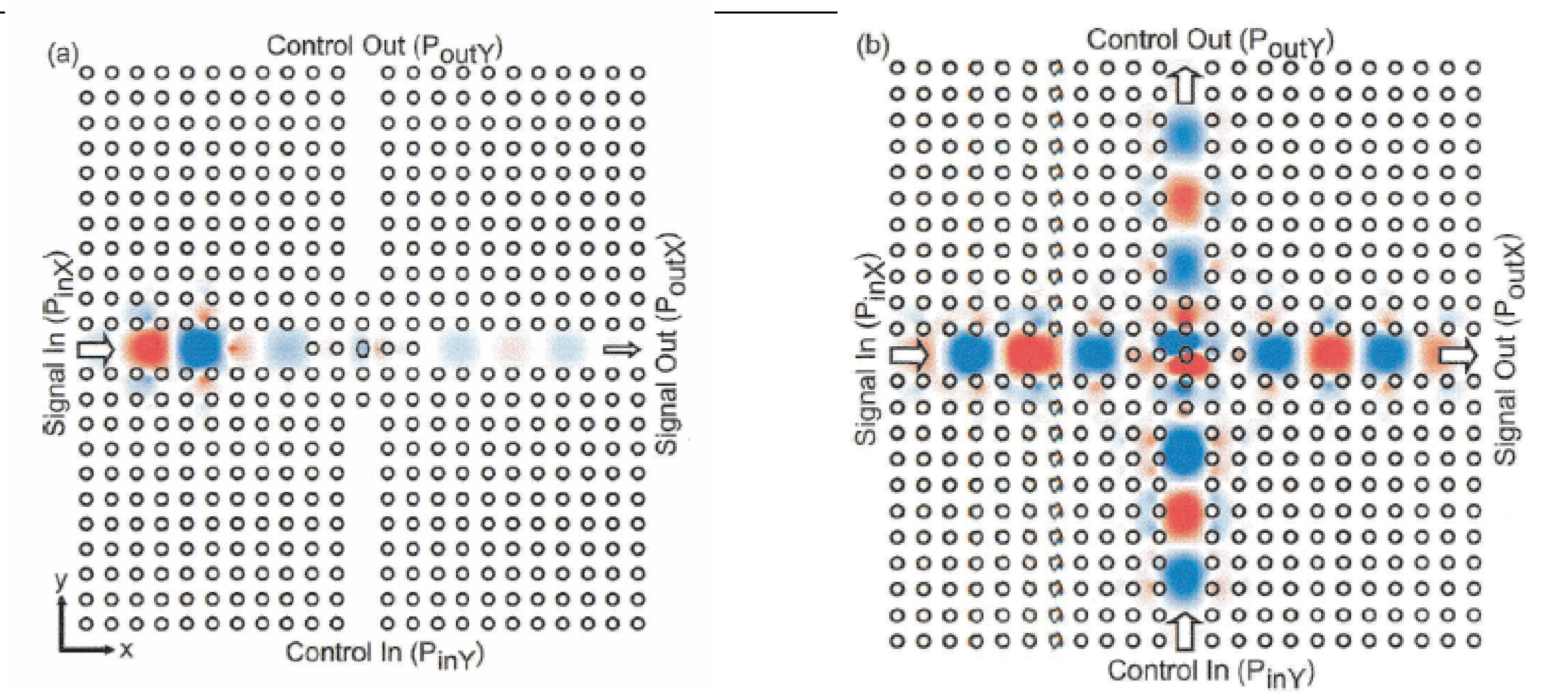




Y. A. Vlasov, et al, *Nature*, 2005

- **Use thermo-optic effect to modulate transmission**
- **Switching speed ~ 100ns (~10MHz)**
- **Power ~ 1mW (~10^5 devices for 100W)**

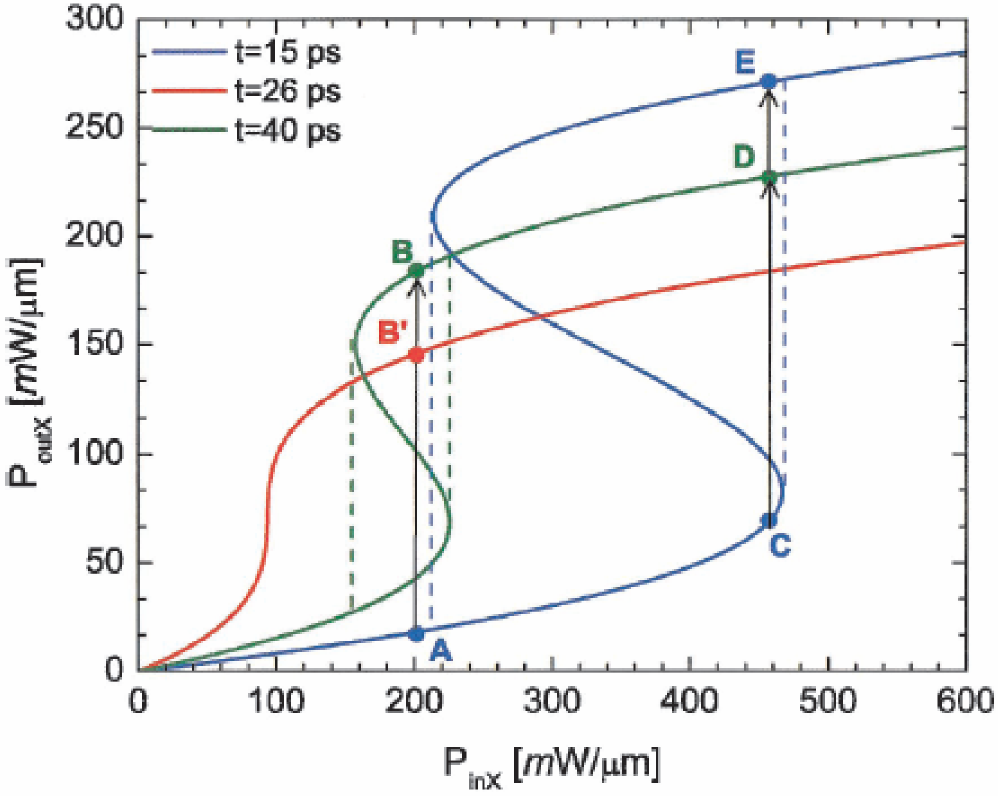
Controlling light with light



M. F. Yanik, et al, *Opt. Lett.*, 2003

- **Two crossing PC waveguides**
- **Use Kerr nonlinearity to control the signal**
- **All-optical transistor operation**

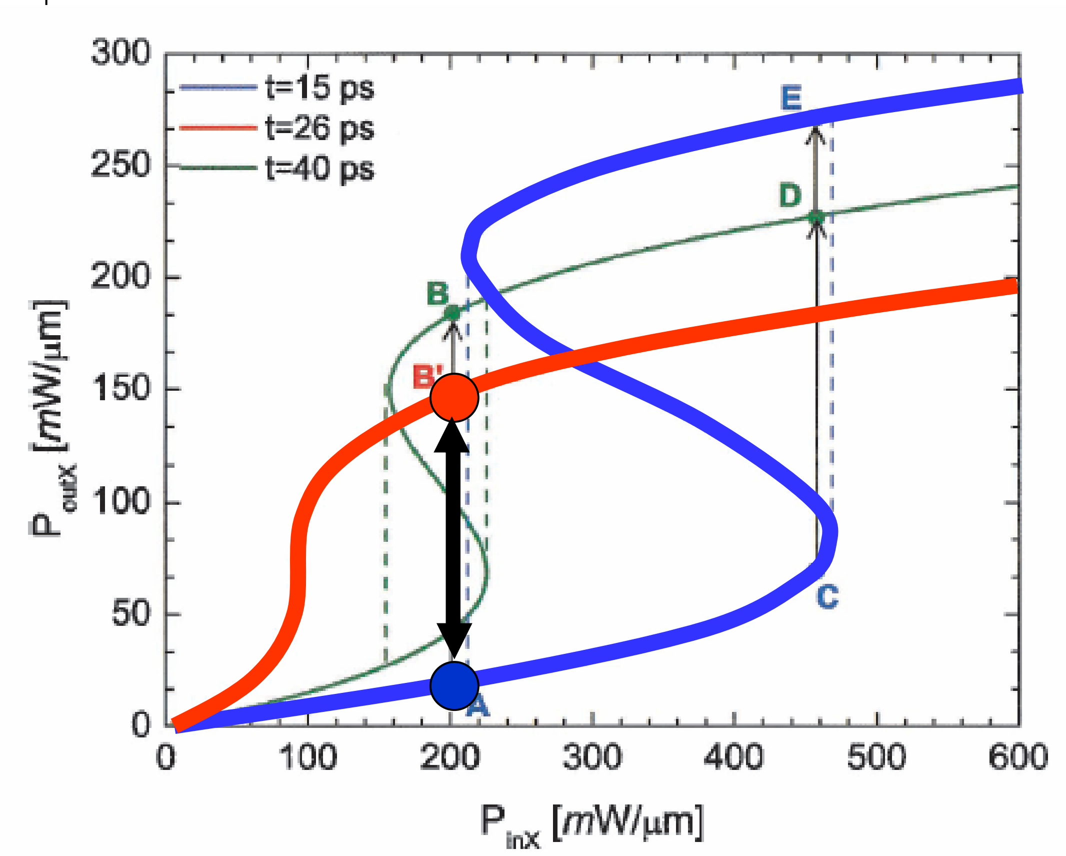
Optical bistability behavior

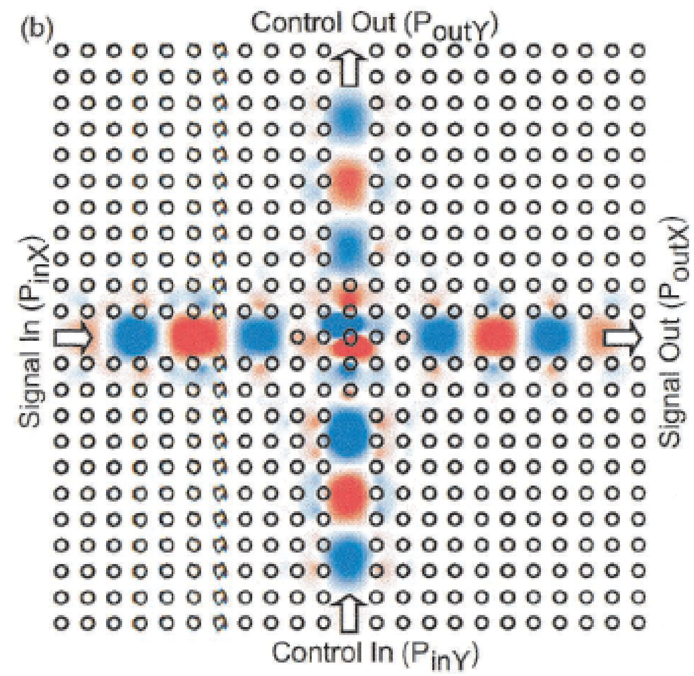


M. F. Yanik, et al, *Opt. Lett.*, 2003

- **Transistor and memory operation**
- **Coupling to the fiber can be done as earlier**

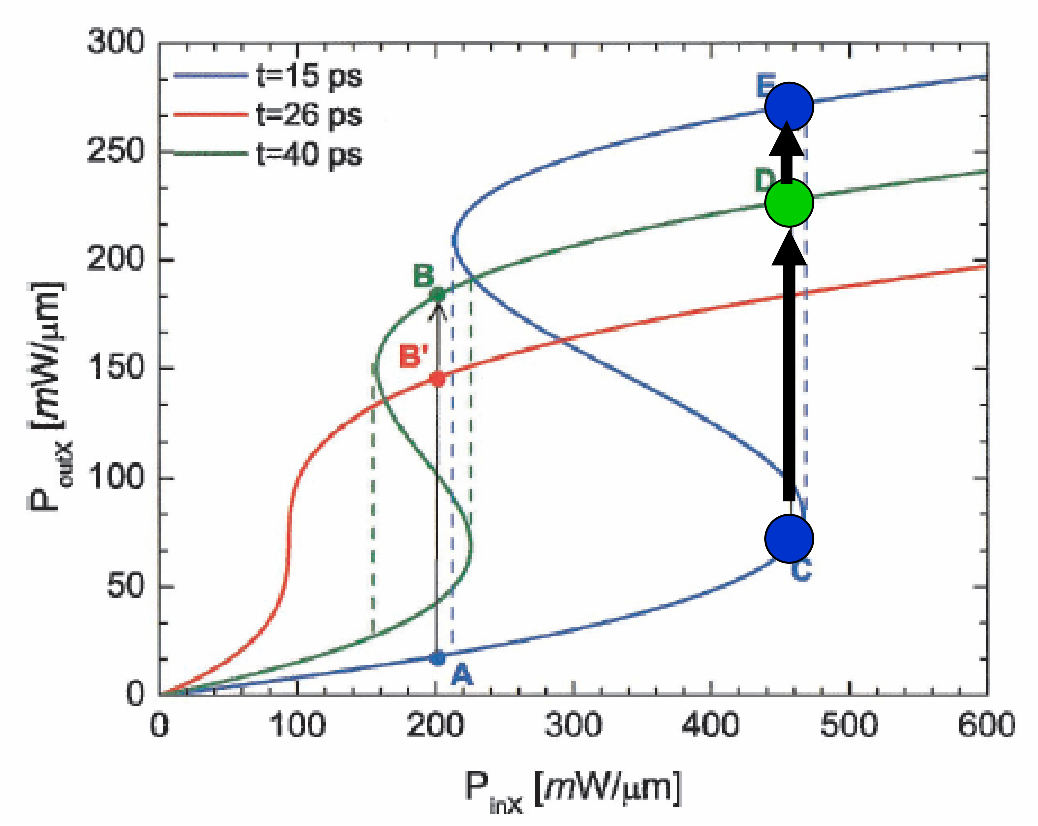
Optical transistor operation





- **Size ~ μm^2**
- **Power ~ mW (~10^5 devices for 100W)**
- **Speed ~ 10GHz**

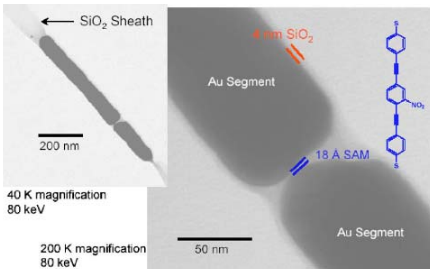
Optical memory effect



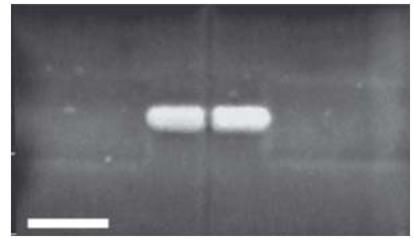
M. F. Yanik, et al, *Opt. Lett.*, 2003

- **Information can be latched**

- Nanoantenna: metal particles of nanometer scale, often paired

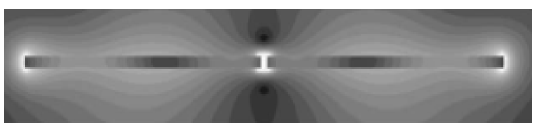


Aizpurua *et al*. Phys. Rev. B, 2005

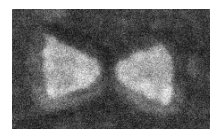


Hecht *et al*. Chimia, 2006

Jain *et al*. Nano Lett., 2007



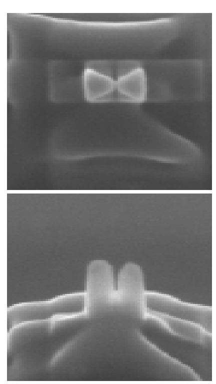
Søndergaard *et al.* Phys. Rev. B, 2007



Fromm *et al*. Nano Lett., 2004

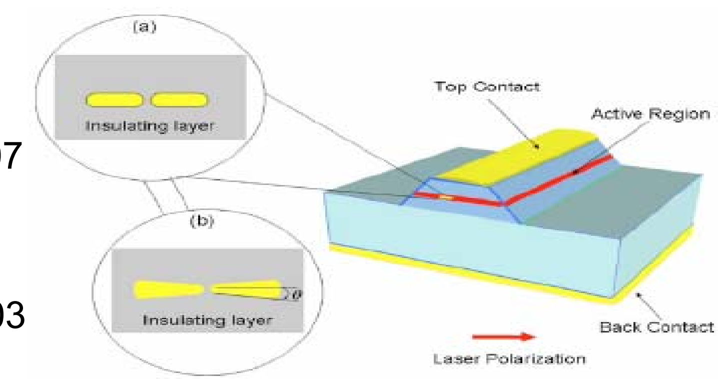
- Applications of nanoantenna: sensors, NSOM, etc.

Farahani *et al.*
Nanotechnology
2007



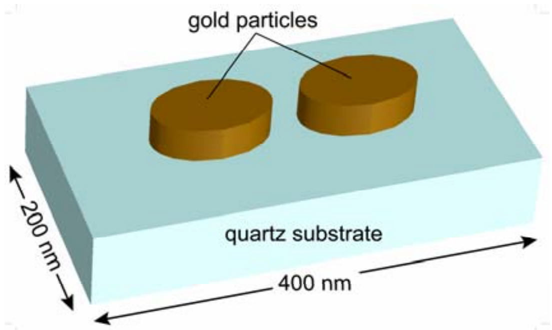
Cubukcu *et al.*
Appl. Phys. Lett., 2007

Bergman, Stockman
Phys. Rev. Lett., 2003

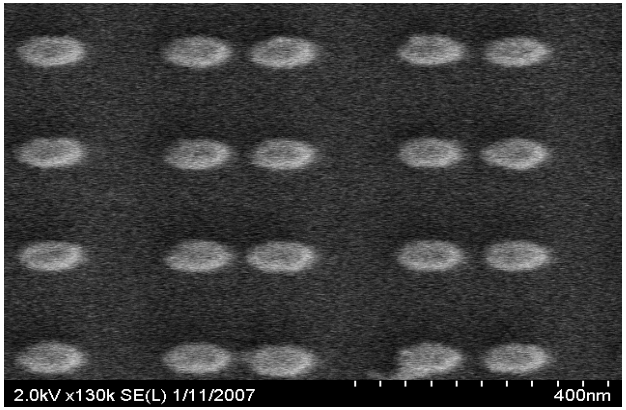


Fabrication and surface characterization

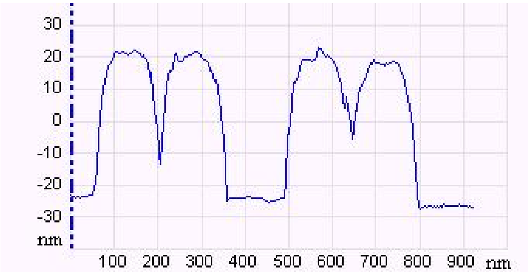
- Fabrication:
  - unit cell: 400 nm × 200 nm
  - Gold Thickness: 40 nm
  - Electron beam lithography



- Scanning electron microscopy (SEM) characterization
  - Major axis ~ 110 nm
  - Minor axis ~ 55 nm
  - Gap ~ 17 nm

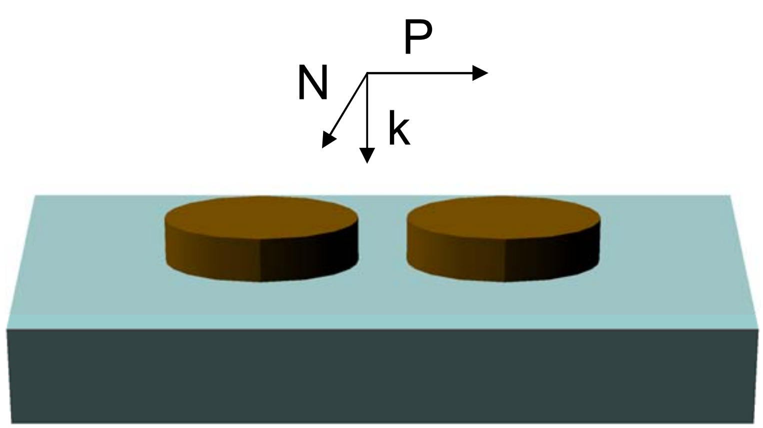


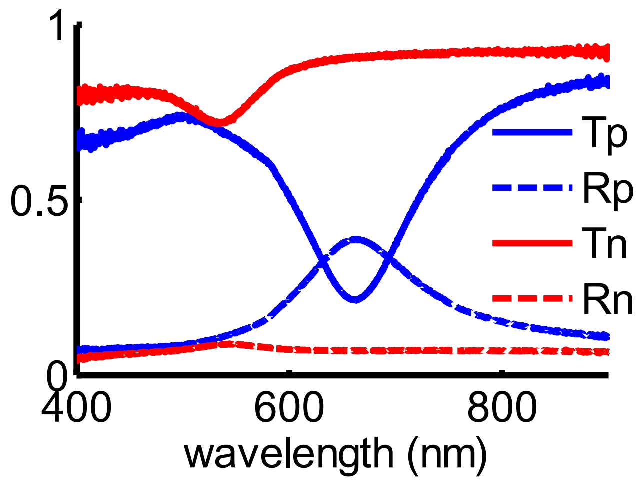
- Atomic force microscopy (AFM)
  - Surface roughness ~ 1 nm



Far-field spectra measurement

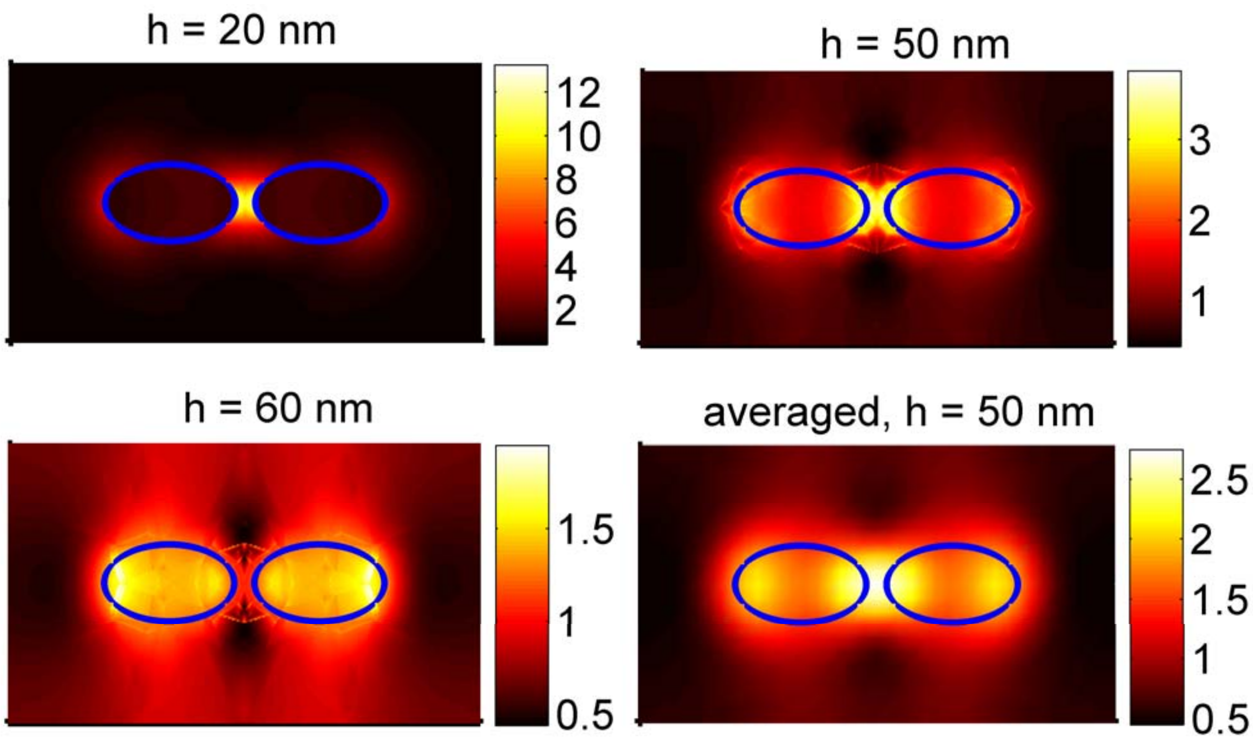
- Far-field transmittance and reflectance measurement: normal incidence, two polarizations
  - Primary polarization (P): electric field parallel to the major axis
  - Secondary polarization (N): electric field normal to the major axis

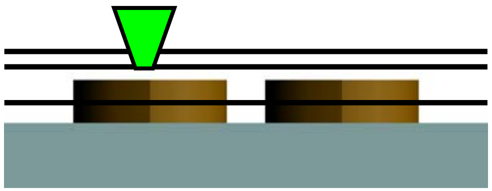




Near field characteristics of nanoantenna

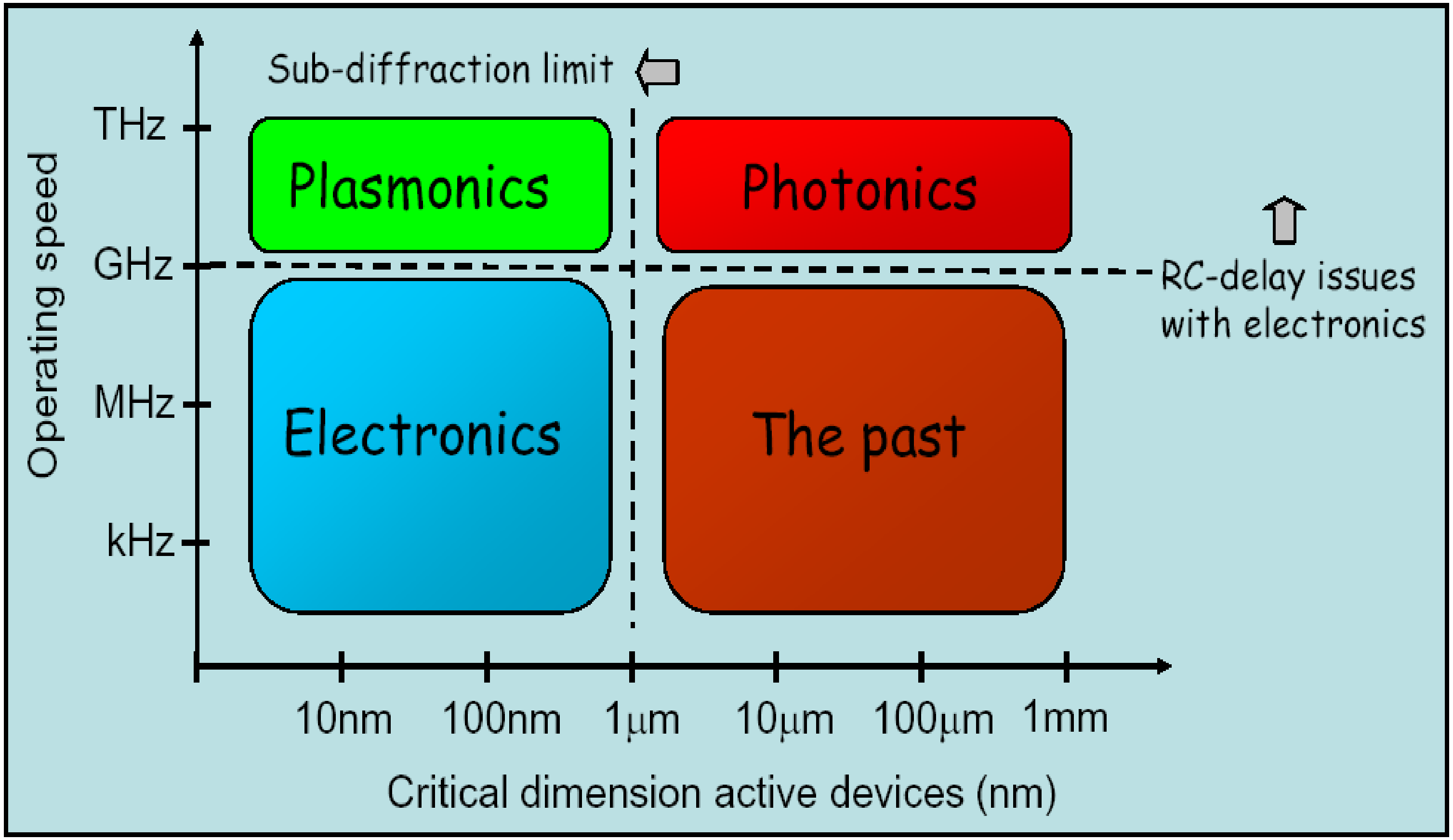
- Field enhancement: strongly localized in 3-D space





Nanophotonics enabled by plasmonics

- Graph of the operating regimes of different technologies



- Plasmonics will enable an improved synergy between electronic and photonic devices
  - Plasmonics naturally interfaces with similar size electronic components
  - Plasmonics naturally interfaces with similar operating speed photonic networks

Courtesy of M. Brongersma