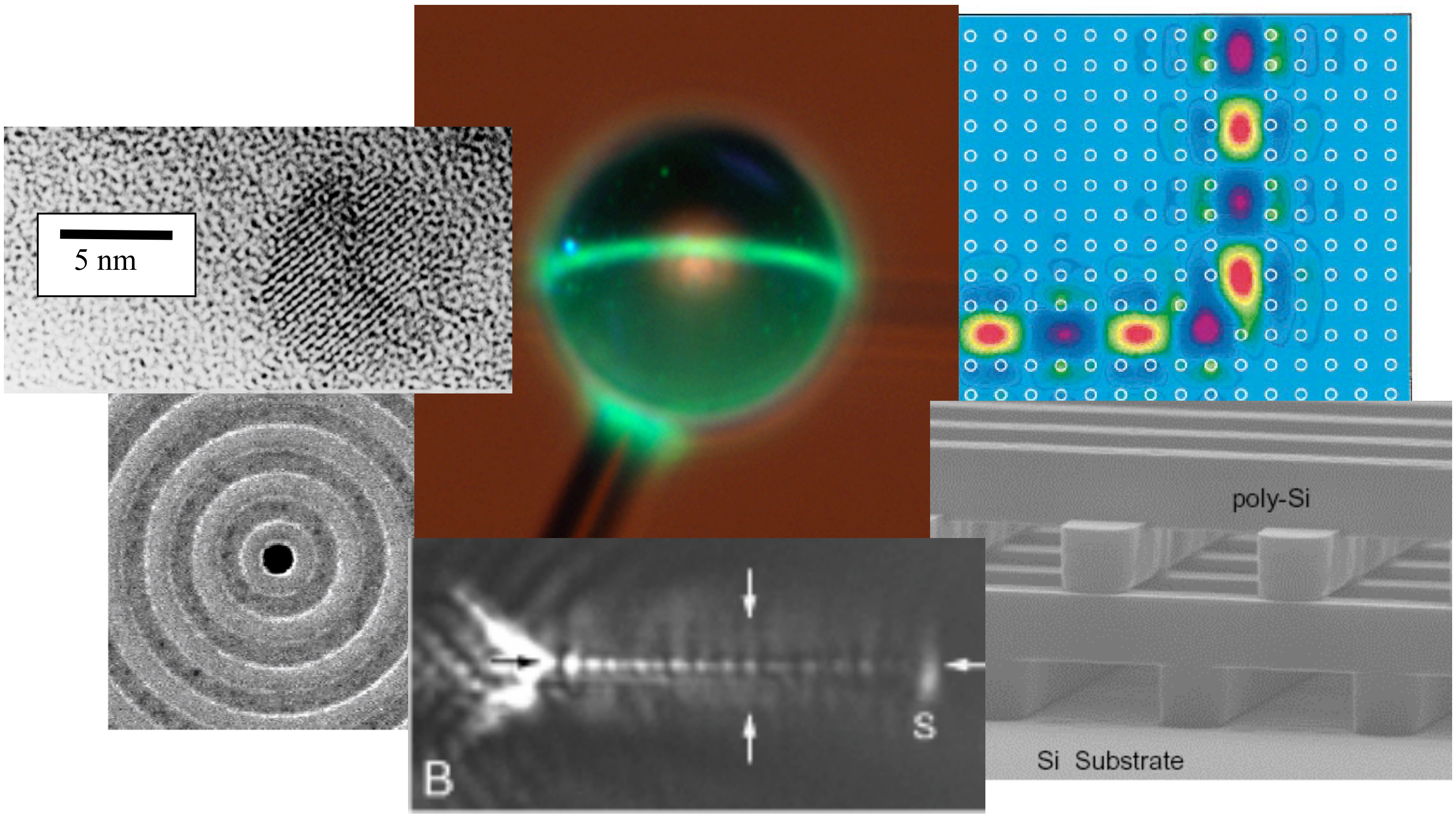
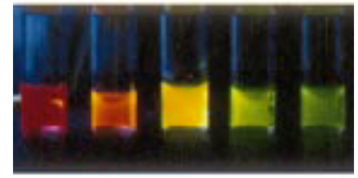
Lecture 9: Introduction to Metal Optics



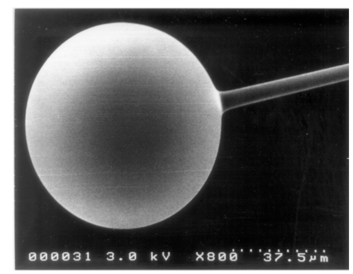
What happened at the previous lectures ?

Light interaction with small objects (d < λ)



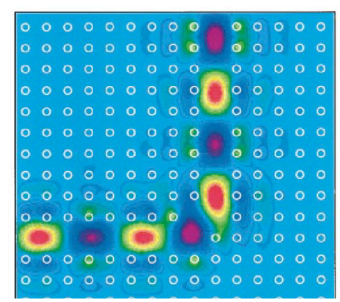
- Insulators (Rayleigh Scattering, blue sky..)
- Semiconductors (Size dependent absorption, fluorescence..)
- Metals…Resonant absorption at ω_{sp}

Microparticles



- Particles with d $\approx$ λ (λ-independent scattering, white clouds)
- Particles with d >> λ (Intuitive ray-picture useful)

Dielectric photonic crystal



- Molding the flow of light

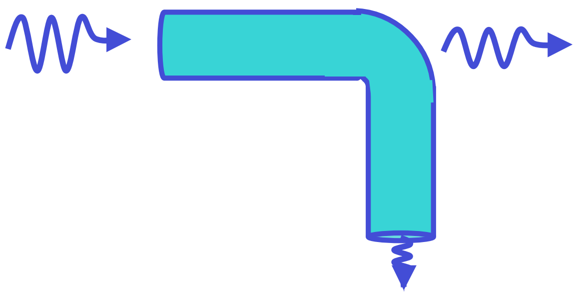
Metal Optics: An Introduction

Majority of optical components based on dielectrics

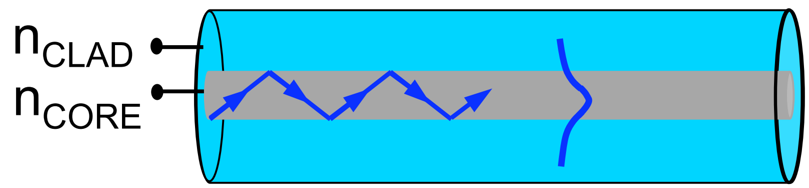
- High speed, high bandwidth (ω), but…
- Does not scale well ⇨ Needed for large scale integration

Problems

Bending losses



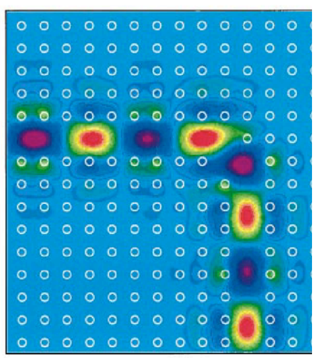
Diffraction Limit



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?!

Plasmon-Polaritons

What is a plasmon ?

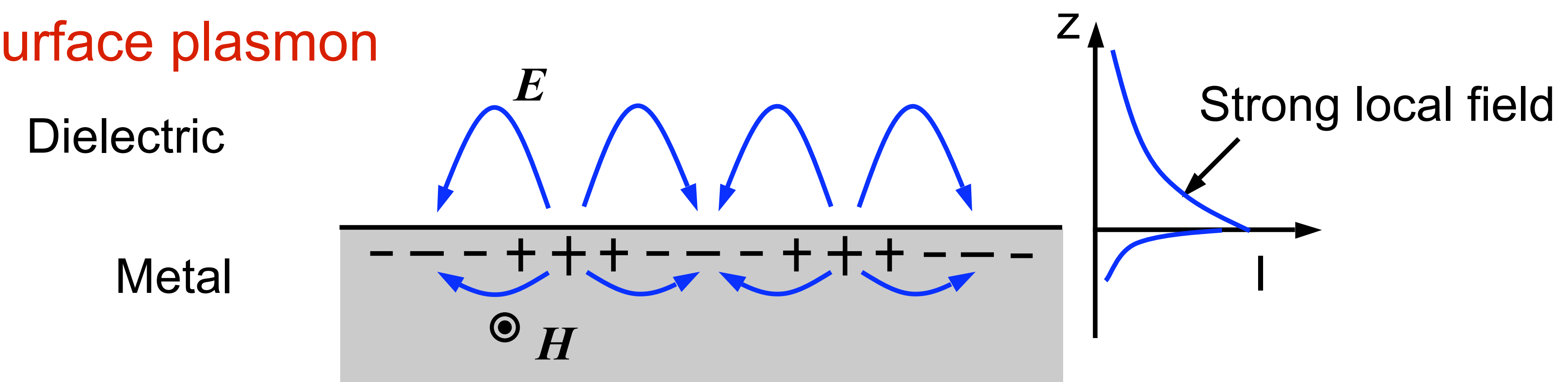
- Compare electron gas in a metal and real gas of molecules
- Metals are expected to allow for electron density waves: plasmons

Bulk plasmon

- Metals allow for EM wave propagation above the plasma frequency

They become transparent!

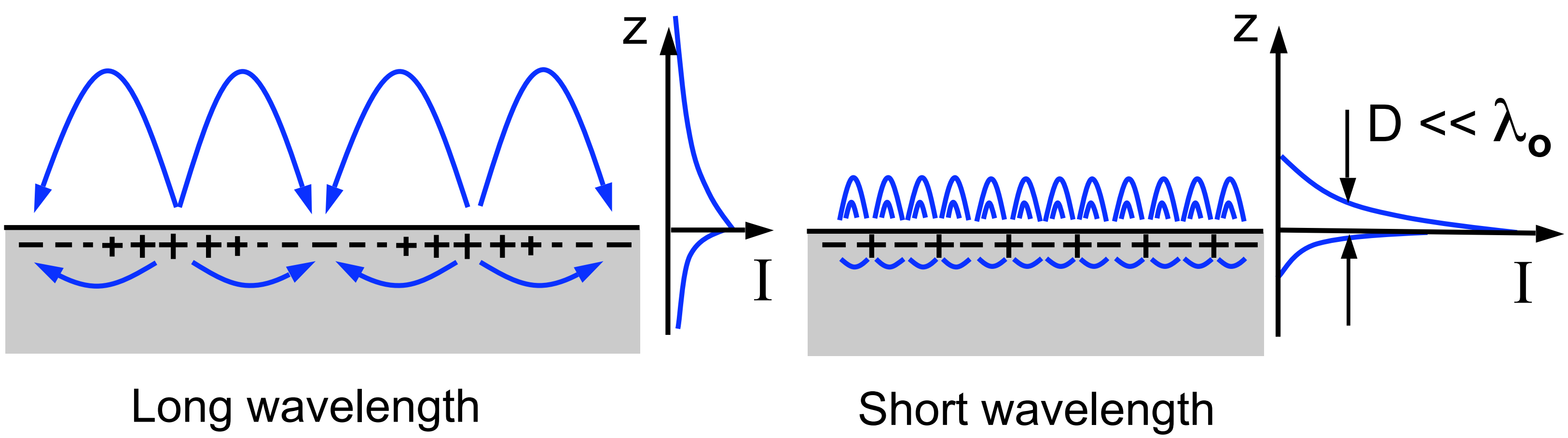
Surface plasmon



Note: This is a TM wave

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

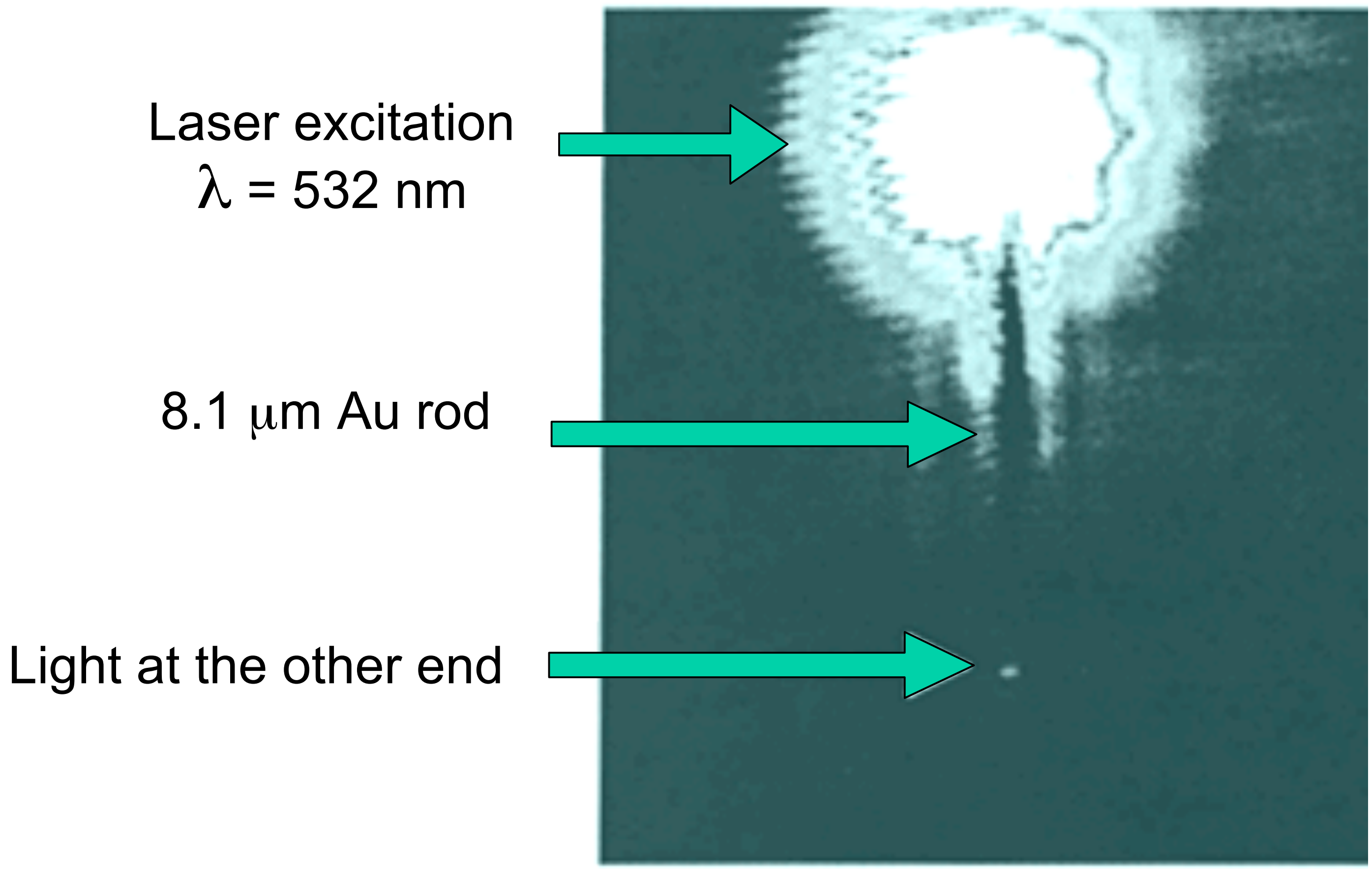
Local Field Intensity Depends on Wavelength



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

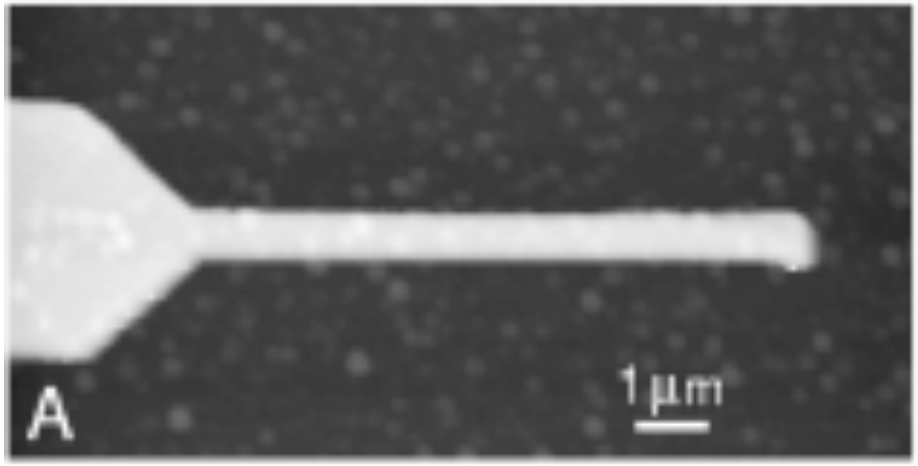
Applications:
- Guiding of light below the diffraction limit (near-field optics)
- Non-linear optics
- Sensitive optical studies of surfaces and interfaces
- Bio-sensors
- Study film growth
- ……

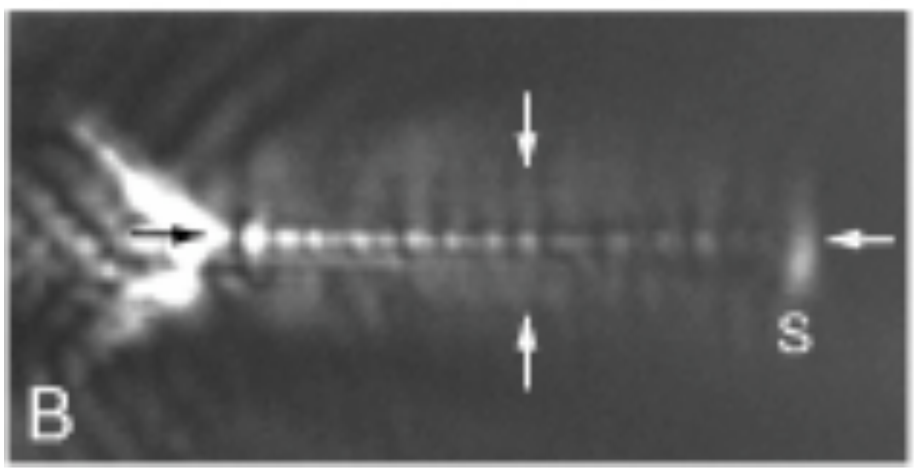
Plasmon-Polariton Propagation in Au rod

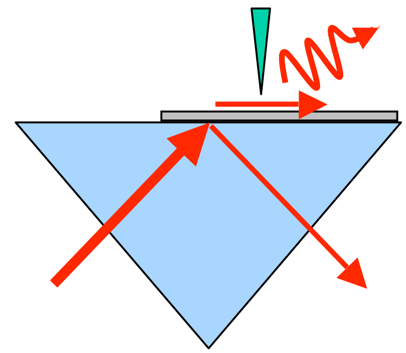


R.M. Dickson and L. A. Lyon, J. Phys. Chem. B ***104****, 6095-6098 (2000)*

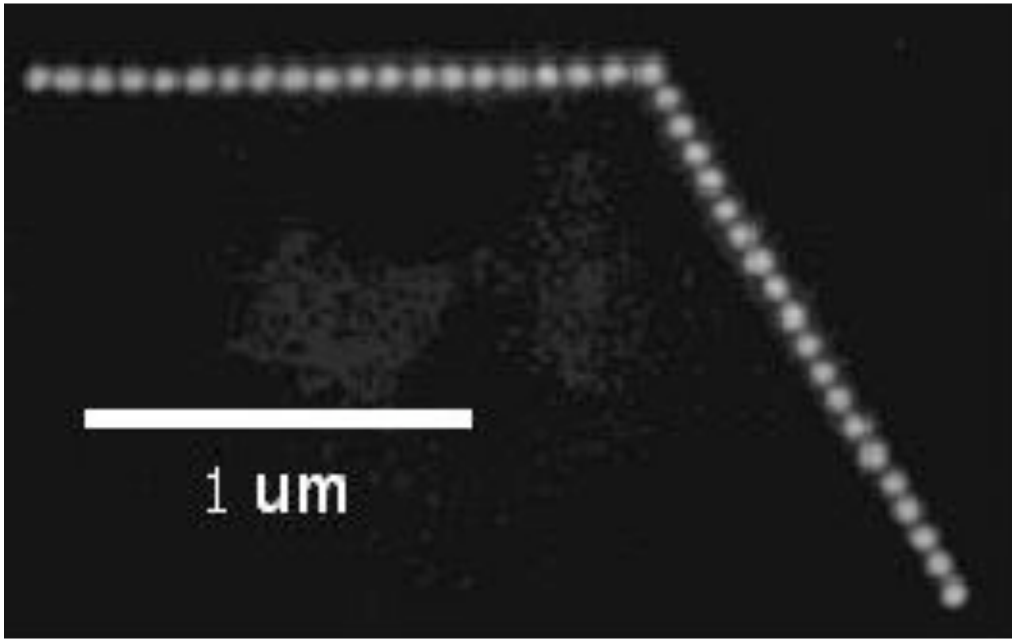
Plasmon-Polariton Excitation using a Launch Pad

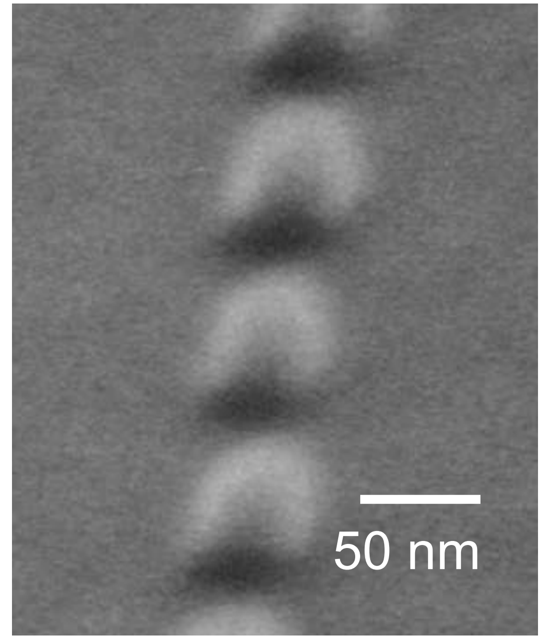






J.R. Krenn et al., Europhys.Lett. ***60, 663-669*** *(2002)*



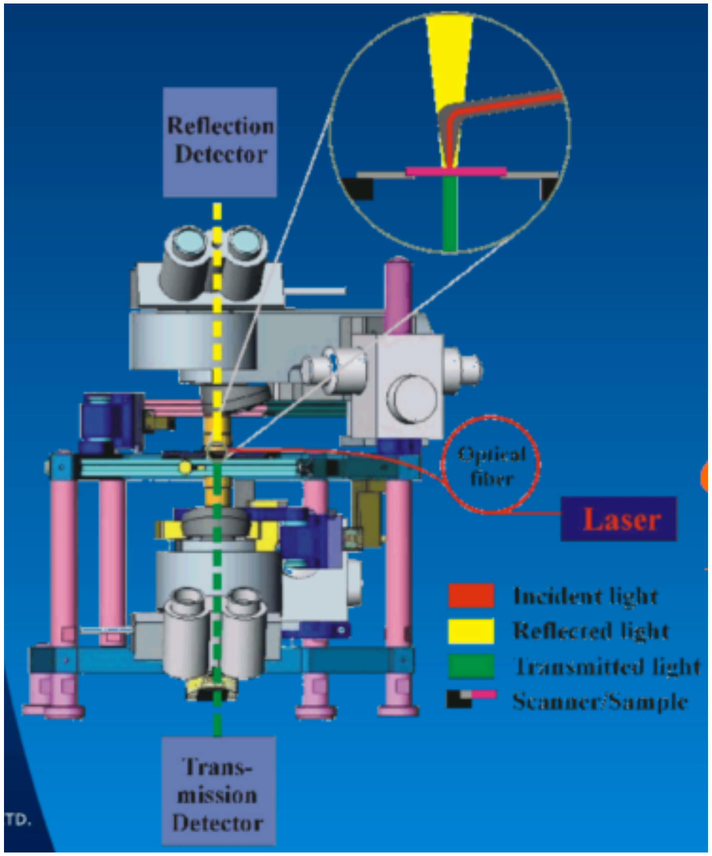


- Array of 50 nanometer diameter Au particles spaced by 75 nanometer
- Guides electromagnetic energy at optical frequency below the diffraction limit
- Enables communication between nanoscale devices
- Information transport at speeds and densities exceeding current electronics

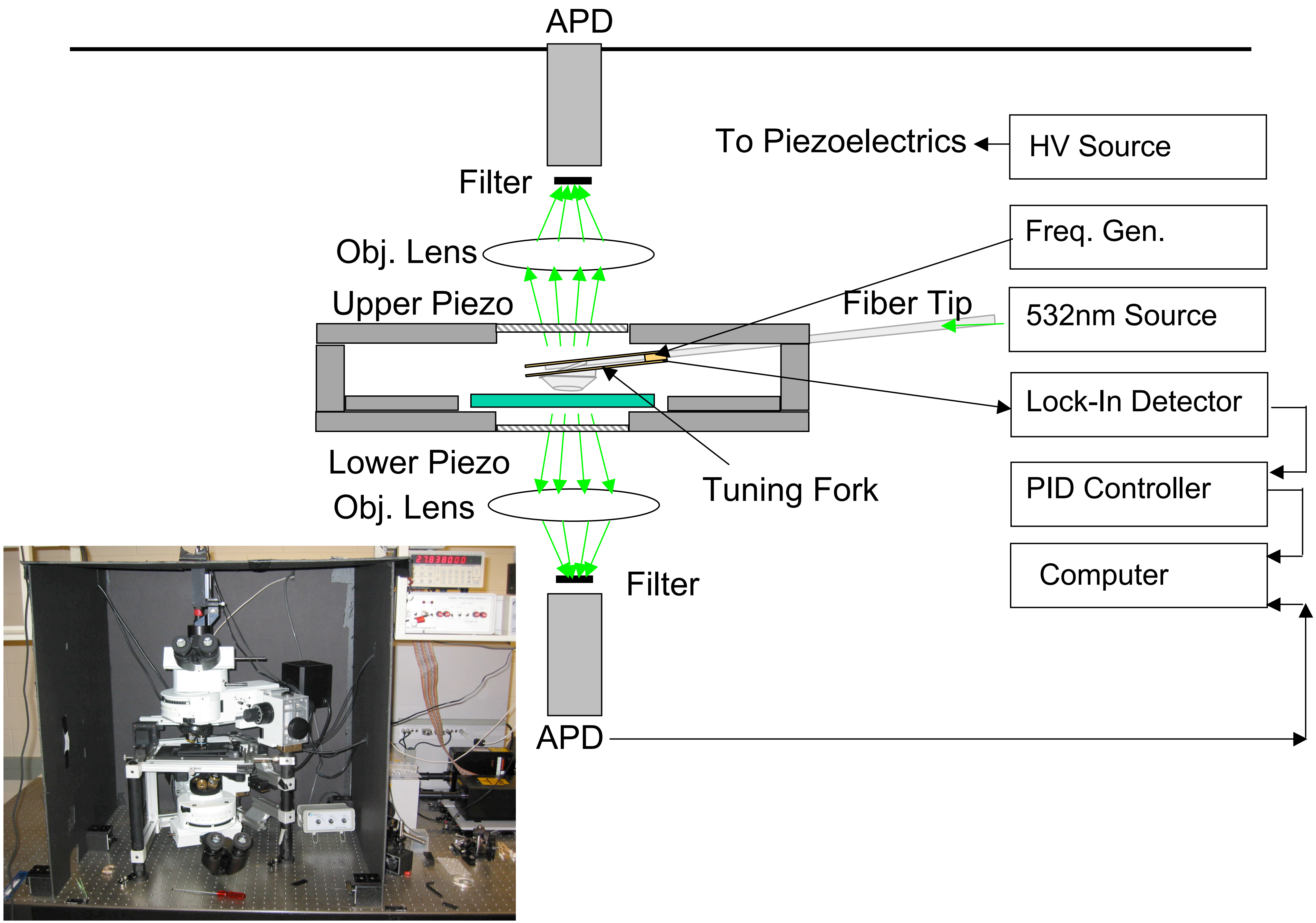
*M.L. Brongersma, et al., Phys. Rev. B **62**, R16356 (2000)*
*S.A. Maier et al., Advanced materials **13**, 1501 (2001)*

Purdue Near-Field Optical Microscope

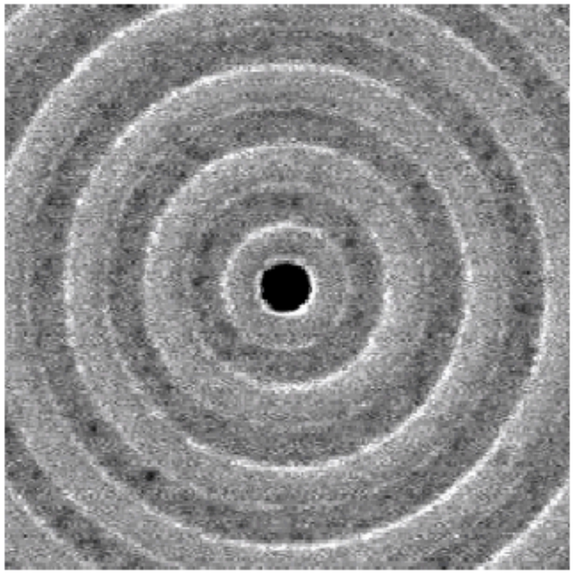
- Nanonics MultiView 2000
- NSOM / AFM
- Tuning Fork Feedback Control
  - Normal or Shear Force
- Aperture tips down to 50 nm
- AFM tips down to 30 nm
- Radiation Source
  - 532 nm

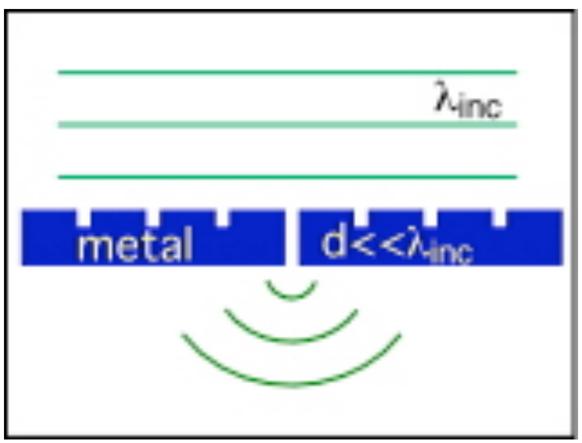


Picture taken from Nanonics


APD
To Piezoelectrics
HV Source
Filter
Freq. Gen.
Obj. Lens
Fiber Tip
Upper Piezo
532nm Source
Lock-In Detector
Lower Piezo
Tuning Fork
PID Controller
Obj. Lens
Computer
Filter
APD

Enhanced Transmission through Sub-λ Apertures





- Ag film with a 440 nm diameter hole surrounded by circular grooves
- Transmission enhancement of 10 x compared to a bare hole
- 3x more light than directly impingent on hole !
- Reason: Excitation of plasmon-polaritons

T.Thio et al., Optics Letters ***26,*** *1972-1974 (2001).*

Optical Properties of an Electron Gas (Metal)

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

- Consider a time varying field: $\mathbf{E}(t) = \mathrm{Re}\left\{\mathbf{E}(\omega)\exp(-i\omega t)\right\}$

- Equation of motion electron (no damping)
- Dipole moment electron

$$\left.\begin{aligned} m\frac{d^2\mathbf{r}}{dt^2} &= -e\mathbf{E} \\ \mathbf{p}(t) &= -e\mathbf{r}(t) \end{aligned}\right\} \Rightarrow m\frac{d^2\mathbf{p}}{dt^2} = e^2\mathbf{E}$$

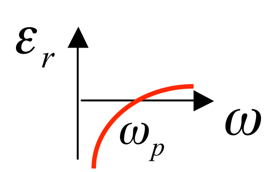
- Harmonic time dependence $\mathbf{p}(t) = \mathrm{Re}\left\{\mathbf{p}(\omega)\exp(-i\omega t)\right\}$

- Substitution **p** into Eq. of motion: $-m\omega^2\mathbf{p}(\omega) = e^2\mathbf{E}(\omega)$

- This can be manipulated into: $\mathbf{p}(\omega) = -\dfrac{e^2}{m}\dfrac{1}{\omega^2}\mathbf{E}(\omega)$

- The dielectric constant is:

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



Dispersion Relation for EM Waves in Electron Gas

Determination of dispersion relation for bulk plasmons

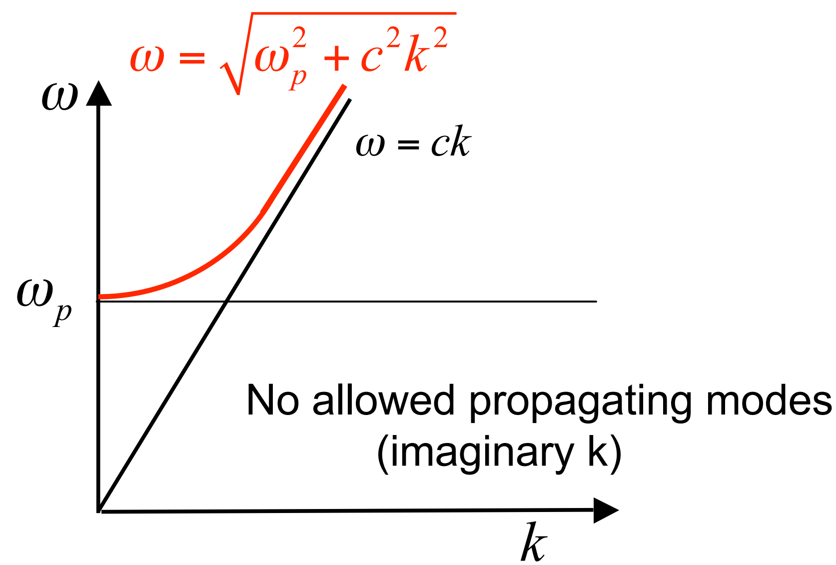
- The wave equation is given by: $$\frac{\varepsilon_r}{c^2}\frac{\partial^2 \boldsymbol{E}(\boldsymbol{r},t)}{\partial \boldsymbol{t}^2} = \nabla^2 \boldsymbol{E}(\boldsymbol{r},t)$$
- Investigate solutions of the form: $$\boldsymbol{E}(\boldsymbol{r},t) = \mathrm{Re}\left\{\boldsymbol{E}(\boldsymbol{r},\omega)\exp\left(i\boldsymbol{k}\cdot\boldsymbol{r}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

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

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

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

- Dispersion relation:



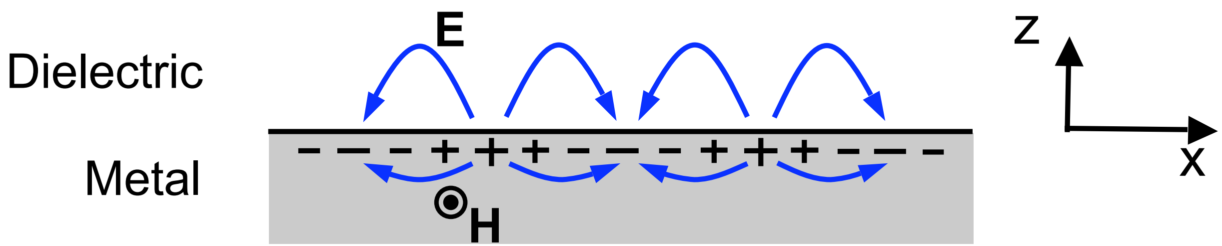
Note1: Solutions lie above light line

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

Dispersion Relation Surface-Plasmon Polaritons

Solve Maxwell's equations with boundary conditions

- We are looking for solutions that look like:



- Mathematically:

z<0

$$\begin{cases} \boldsymbol{H}_d = (0, H_{yd}, 0)\exp i\left(k_{xd}x + k_{zd}z - \omega t\right) \\ \boldsymbol{E}_d = (E_{xd}, 0, E_{zd})\exp i\left(k_{xd}x + k_{zd}z - \omega t\right) \end{cases}$$

z>0

$$\begin{cases} \boldsymbol{H}_m = (0, H_{ym}, 0)\exp i\left(k_{xm}x + k_{zm}z - \omega t\right) \\ \boldsymbol{E}_m = (E_{xm}, 0, E_{zm})\exp i\left(k_{xm}x + k_{zm}z - \omega t\right) \end{cases}$$

- Maxwell's Equations in medium i (i = metal or dielectric):

$$\nabla \cdot \varepsilon_i \boldsymbol{E} = 0 \qquad \nabla \cdot \boldsymbol{H} = 0 \qquad \nabla \times \boldsymbol{E} = -\mu_0 \frac{\partial \boldsymbol{H}}{\partial \boldsymbol{t}} \qquad \nabla \times \boldsymbol{H} = \varepsilon_i \frac{\partial \boldsymbol{E}}{\partial \boldsymbol{t}}$$

- At the boundary:

$$E_{x,m} = E_{x,d} \qquad \varepsilon_m E_{zm} = \varepsilon_d E_{zm} \qquad H_{ym} = H_{yd}$$

Dispersion Relation Surface-Plasmon Polaritons

- Start with curl equation for $\boldsymbol{H}$ in medium i (as we did for EM waves in vacuum)

$$\left.\begin{aligned} &\nabla \times \boldsymbol{H}_i = \varepsilon_i \frac{\partial \boldsymbol{E}_i}{\partial \boldsymbol{t}} \\ \text{where}\quad &\boldsymbol{H}_i = \left(0, H_{yi}, 0\right)\exp i\left(k_{xi}x + k_{zi}z - \omega t\right) \\ &\boldsymbol{E}_i = \left(E_{xi}, 0, E_{zi}\right)\exp i\left(k_{xi}x + k_{zi}z - \omega t\right) \end{aligned}\right\} \Rightarrow$$

$$\left(\frac{\partial H_{zi}}{\partial y} - \frac{\partial H_{yi}}{\partial z}, \frac{\partial H_{xi}}{\partial z} - \frac{\partial H_{zi}}{\partial x}, \frac{\partial H_{yi}}{\partial x} - \frac{\partial H_{xi}}{\partial y}\right) = \left(\underline{ik_{zi}H_{yi}}, 0, ik_{xi}H_{yi}\right) = \left(\underline{-i\omega\varepsilon_i E_{xi}}, 0, i\omega\varepsilon_i E_{zi}\right)$$

- We will use that: $k_{zi}H_{yi} = -\omega\varepsilon_i E_{xi} \Rightarrow \begin{cases} k_{zm}H_{yi} = -\omega\varepsilon_m E_{xm} \\ k_{zd}H_{yd} = -\omega\varepsilon_d E_{xd} \end{cases}$

- $E_{//}$ across boundary is continuous: $E_{x,m} = E_{x,d}$

$$\Rightarrow \frac{k_{zm}}{\varepsilon_m}H_{ym} = \frac{k_{zd}}{\varepsilon_d}H_{yd}$$

- $H_{//}$ across boundary is continuous: $H_{ym} = H_{yd}$

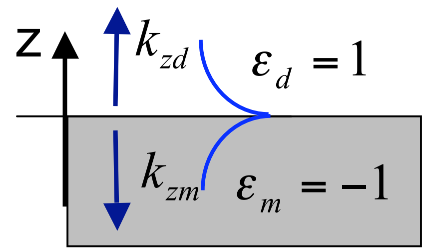
Combine with: $\dfrac{k_{zm}}{\varepsilon_m}H_{ym} = \dfrac{k_{zd}}{\varepsilon_d}H_{yd}$

$$\Rightarrow \boxed{\frac{k_{zm}}{\varepsilon_m} = \frac{k_{zd}}{\varepsilon_d}}$$

Dispersion Relation Surface-Plasmon Polaritons

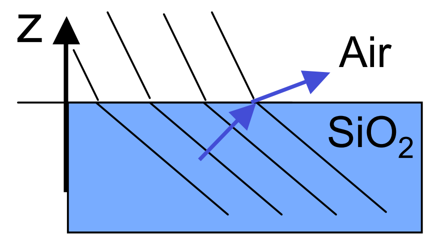
Relations between k vectors

- Condition for SP's to exist: $\dfrac{k_{zm}}{\varepsilon_m} = \dfrac{k_{zd}}{\varepsilon_d}$ Example



- Relation for k_x (Continuity $E_{//}$, $H_{//}$) : $k_{xm} = k_{xd}$ Example

true at any boundary



- For any EM wave: $k_x^2 + k_{zi}^2 = \varepsilon_i \left(\dfrac{\omega}{c}\right)^2$

- Both in the metal and dielectric: $k_{sp} = k_x = \sqrt{\varepsilon_i \left(\dfrac{\omega}{c}\right)^2 - k_{zi}^2}$

$$\frac{k_{zm}}{\varepsilon_m} = \frac{k_{zd}}{\varepsilon_d}$$

Dispersion relation

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

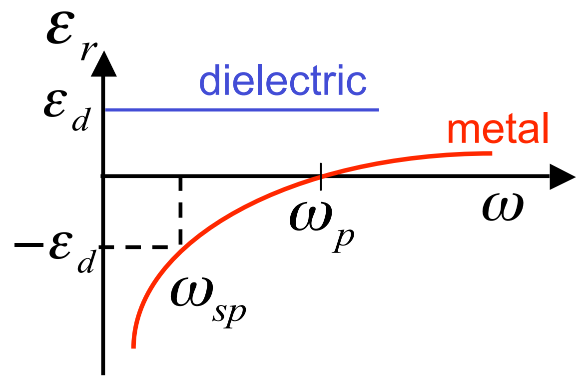
homework

Dispersion Relation Surface-Plasmon Polaritons

Plot of the dispersion relation

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

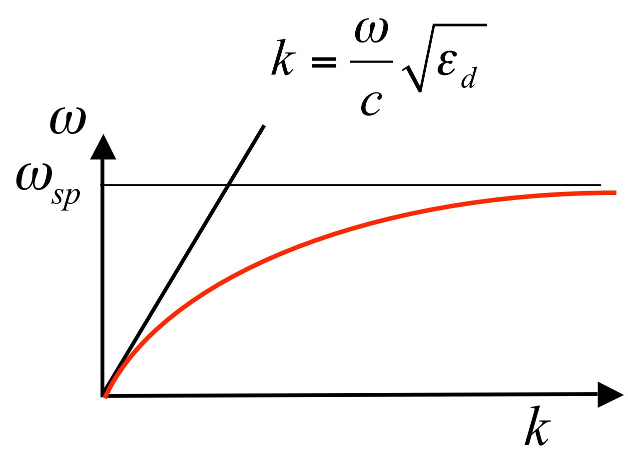
- Plot dielectric constants



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

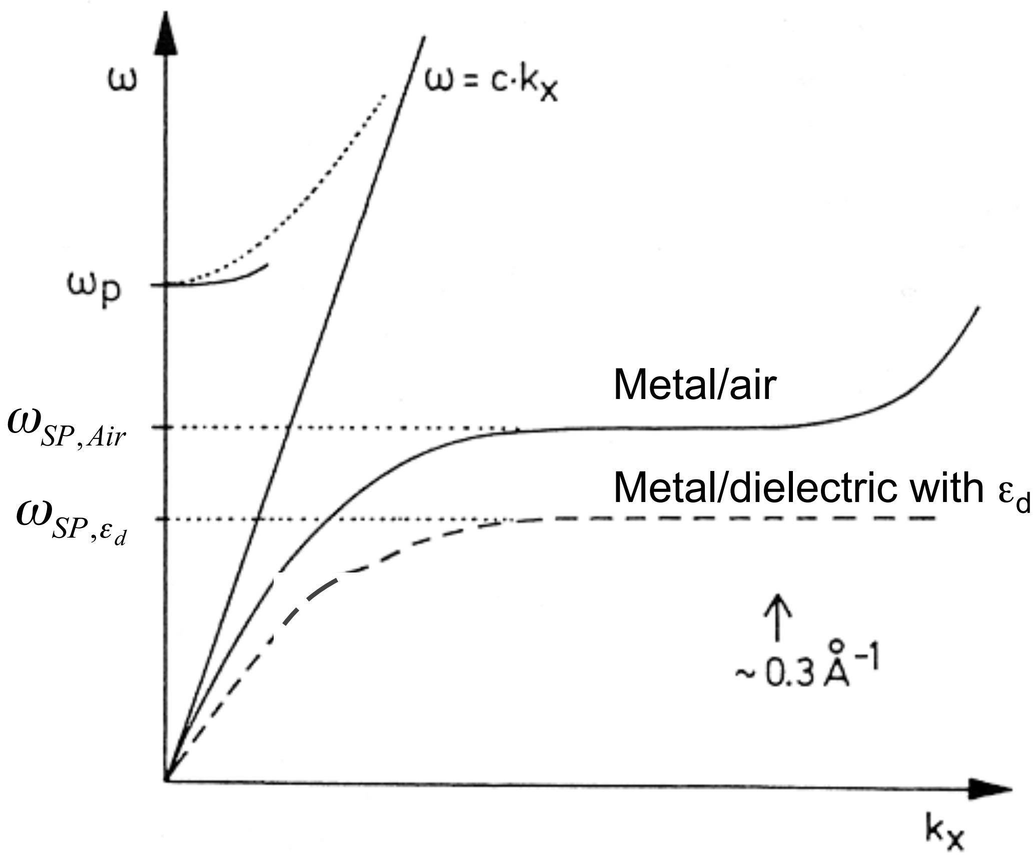
- At $\omega = \omega_{sp}$ (when $\varepsilon_m = -\varepsilon_d$): $k_x \to \infty$

- Note: Solution lies below the light line



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: $\varepsilon_m = 1 - \dfrac{\omega_p^2}{\omega^2} = -\varepsilon_d \Rightarrow \omega^2 - \omega_p^2 = -\varepsilon_d \omega^2 \Rightarrow \omega^2 = \dfrac{\omega_p^2}{1+\varepsilon_d} \Rightarrow \omega = \dfrac{\omega_p}{\sqrt{1+\varepsilon_d}}$

Excitation Surface-Plasmon Polaritons with Electrons

Excitation with electrons

- First experiments with high energy electrons
- Measurement: Energy loss
  Direction of e's:

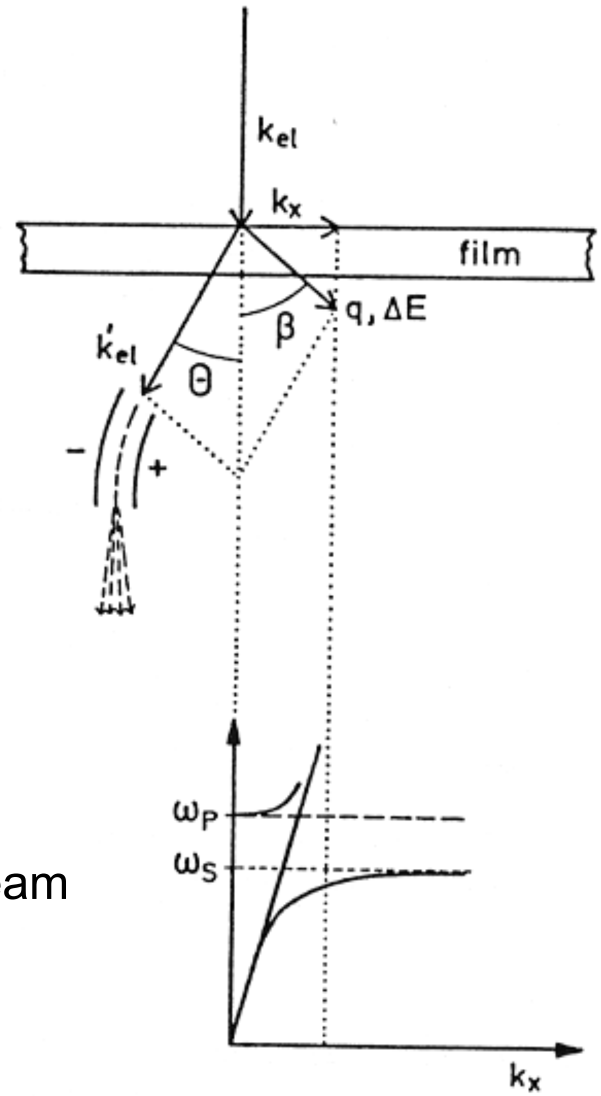
- Whole dispersion relation can be investigated

- Low k's are hard!

Example: 50 keV has a λ = 0.005 nm << λ_{light}

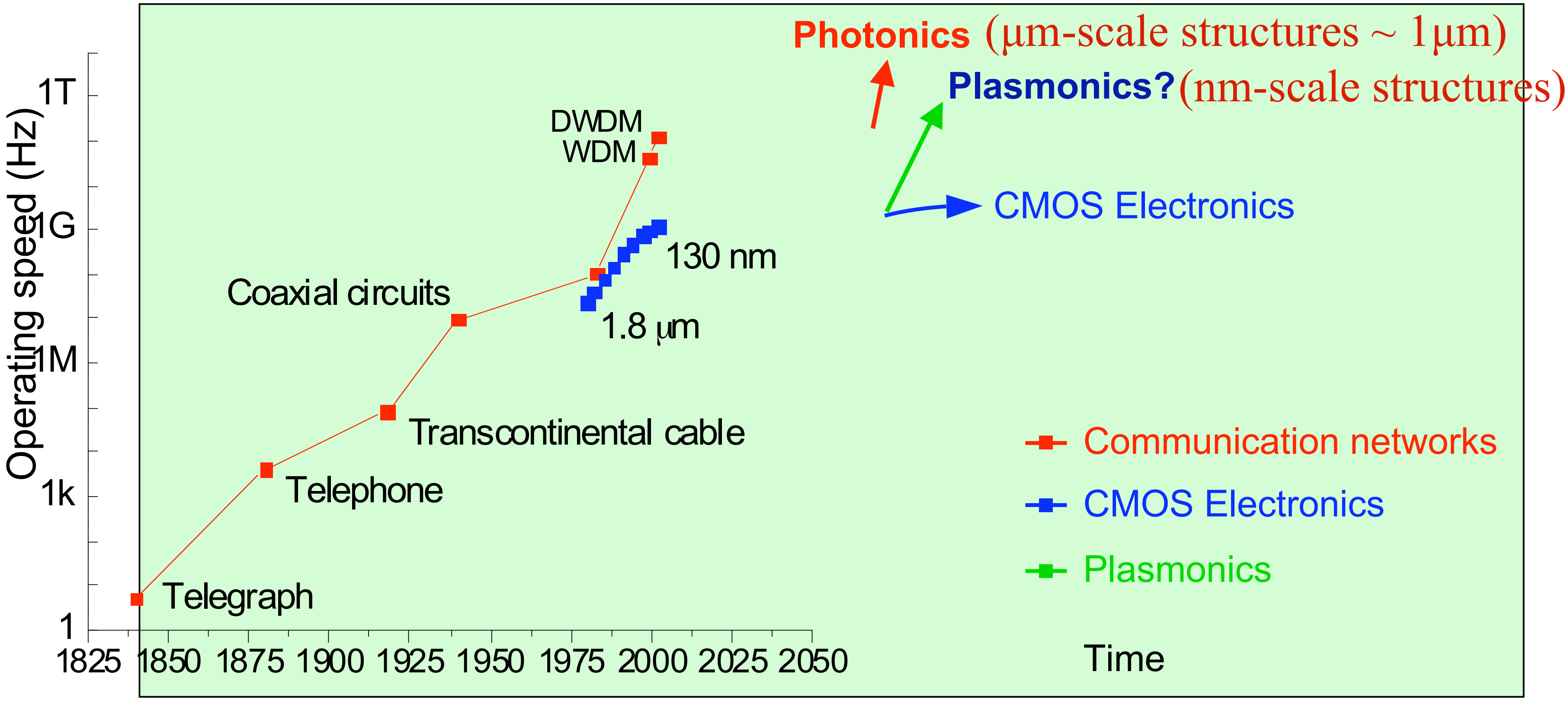
⇨ $k_{electron} >> k_{light}$

⇨ Stringent requirement on divergence e^- beam



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

Why not electronics?

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

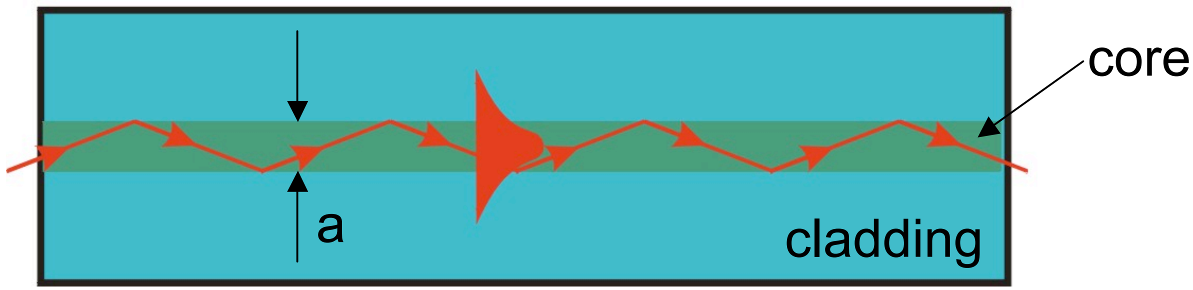
$$R \propto L/A \quad \oplus \quad C \propto L \quad \Rightarrow \quad B_{\max} \propto \frac{1}{RC} \propto \frac{A}{L^2}$$

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

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:**

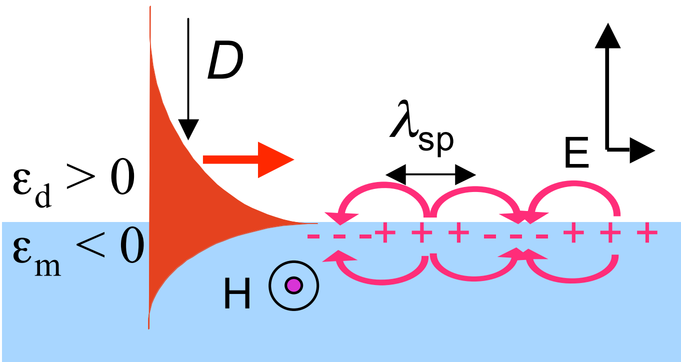


$$n_{core} = n_{clad} + \delta n = n + \delta n \;\Rightarrow\; V = \frac{2\pi}{\lambda} a \sqrt{n_{core}^2 - n_{clad}^2} \cong \frac{2\partial}{\ddot{e}} \mathrm{a}\sqrt{2n\delta n}$$

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

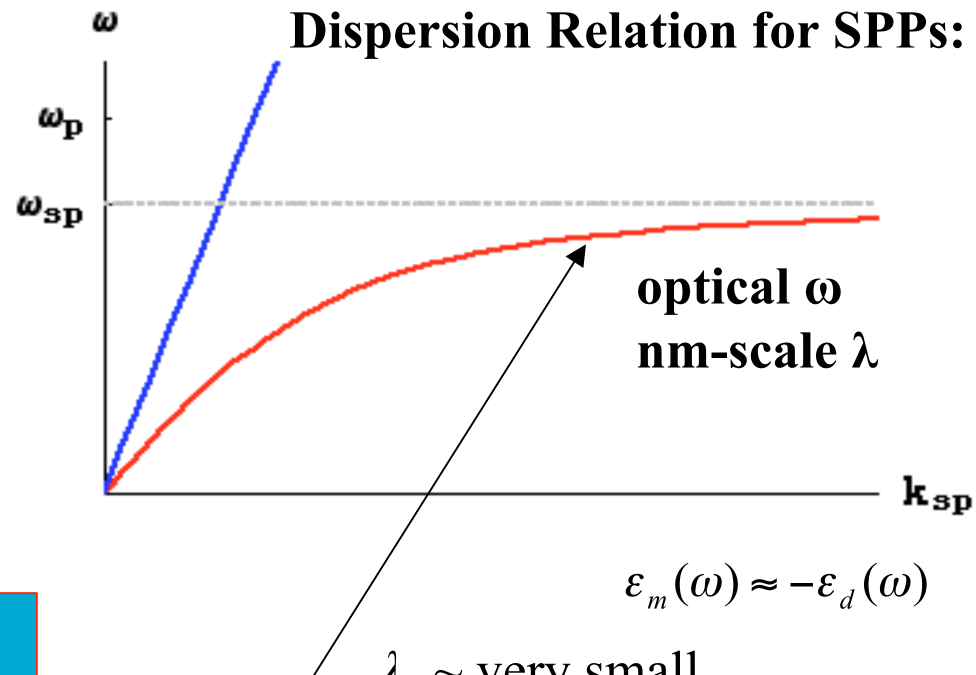
Photonics is diffraction- *<u>limited in size</u>*!

Why Plasmonics?



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

Dispersion Relation for SPPs:



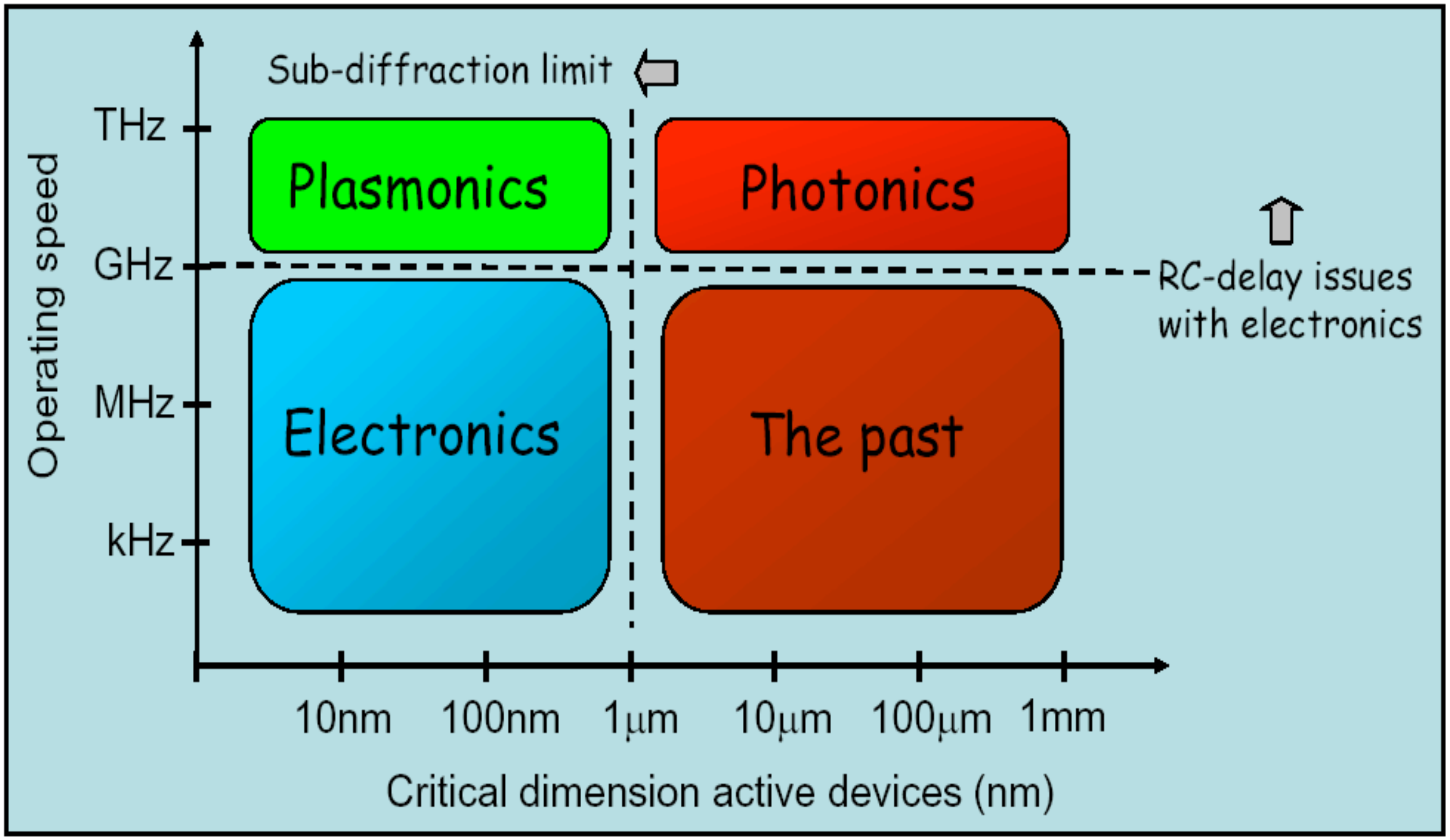
$\varepsilon_m(\omega) \approx -\varepsilon_d(\omega)$

$\lambda_p \sim$ very small

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

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