Super-Diffraction Limited Wide Field Imaging and Microfabrication Based on Plasmonics

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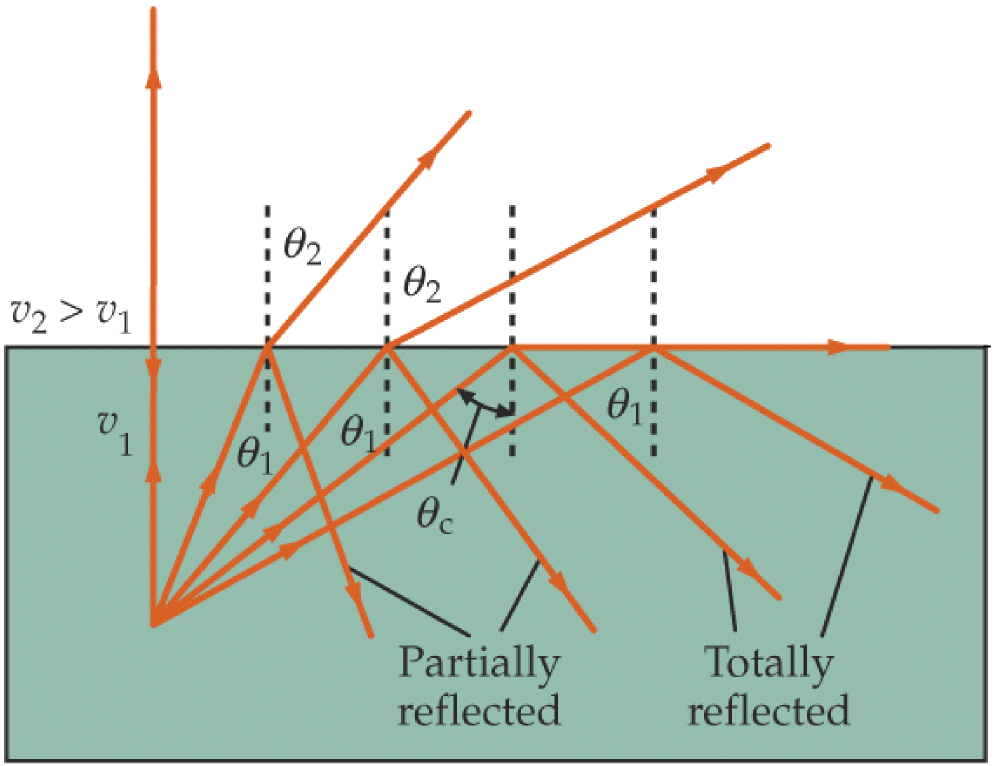
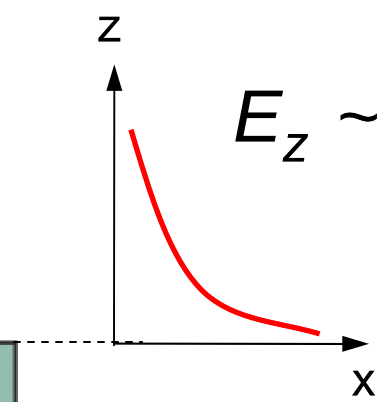
Overview

- Background
  - Total internal reflection
- Motivation
- Theory
  - Surface Plasmon and Photon coupling
- Experimental Setup
- Experiment & Results
- Future work

Total internal reflection (TIR)



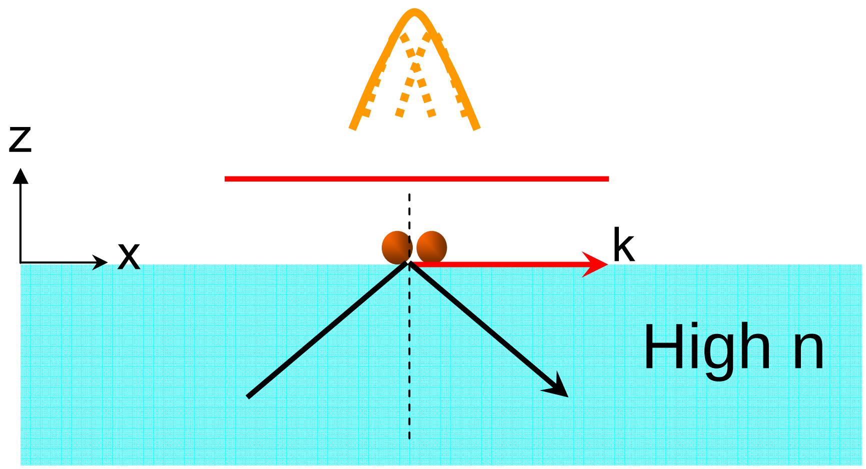


$$E_z \sim e^{-|k_z|z}$$

$$E = E_0 \exp\left[i(k_x x + k_z z - \omega t)\right]$$

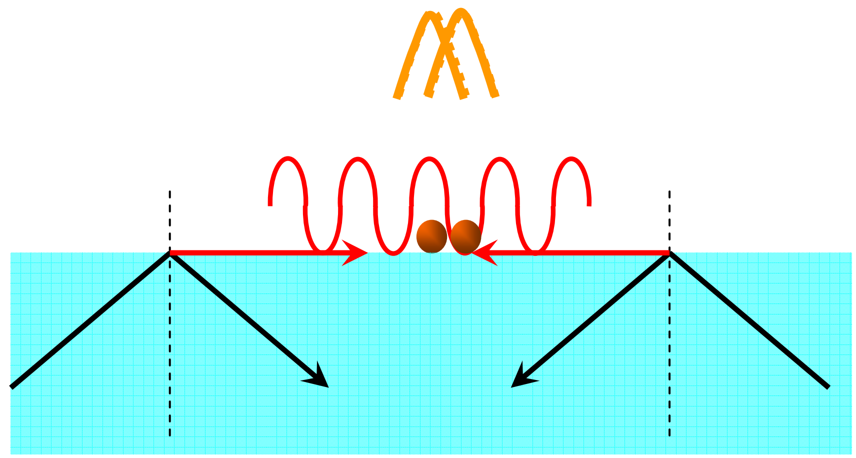
(http://qbx6.ltu.edu)

TIR imaging



$$I(x) = \left| E e^{i(kx-\omega t)} \right|^2 = E^2$$

Uniform excitation



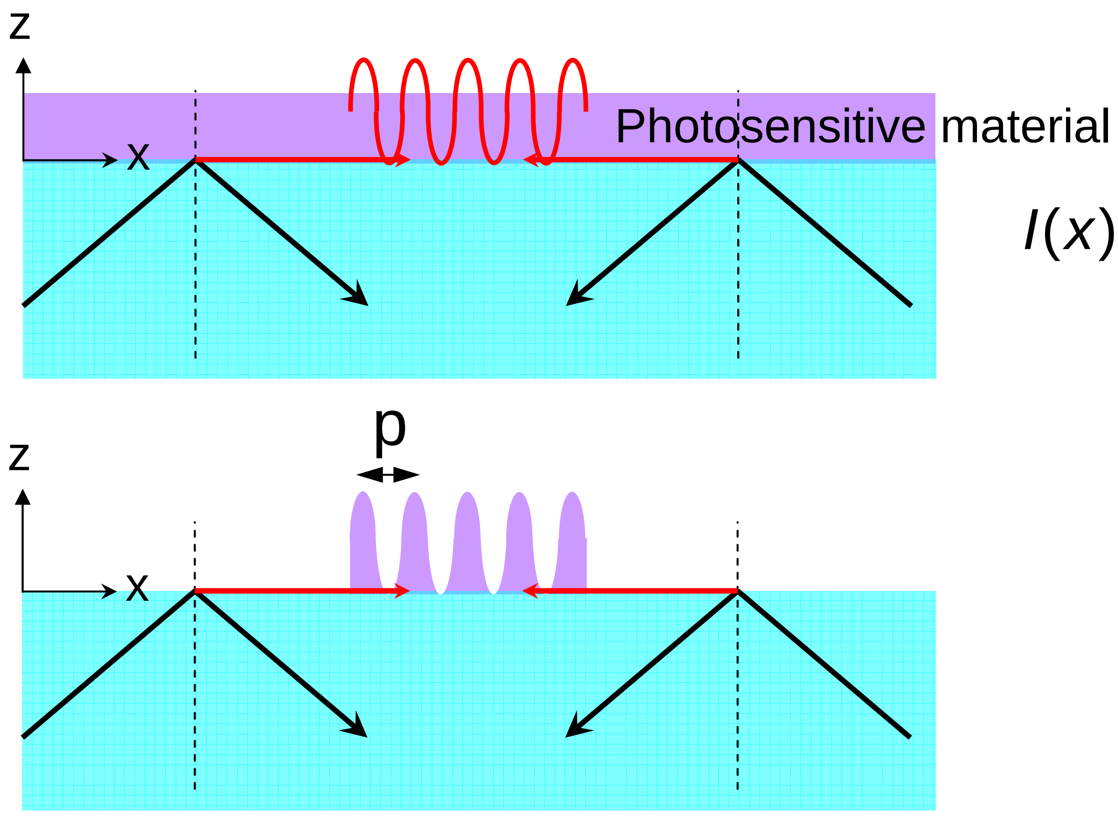
$$\boldsymbol{I(x)} = \left| E e^{i(kx-\omega t)-\phi} + E e^{i(-kx-\omega t)} \right|^2$$

$$= 2E^2 [1 + \cos(2kx + \phi)]$$

Standing wave excitation

(Chung et al., Opt. Lett., 2006)

TIR lithography



$$I(x) = 2E^2[1 + \cos(2kx)]$$

$$k = \frac{2\pi n \sin\theta}{\lambda}$$

$$p = \lambda / (2n \sin\theta)$$

(Ecoffet et al., Adv. Mater., 1998)

p: period of the pattern, n: refractive index

Motivation

Total internal reflection (TIR) of light

Interference of Two Evanescent Waves

Surface Plasmon Resonance (SPR)

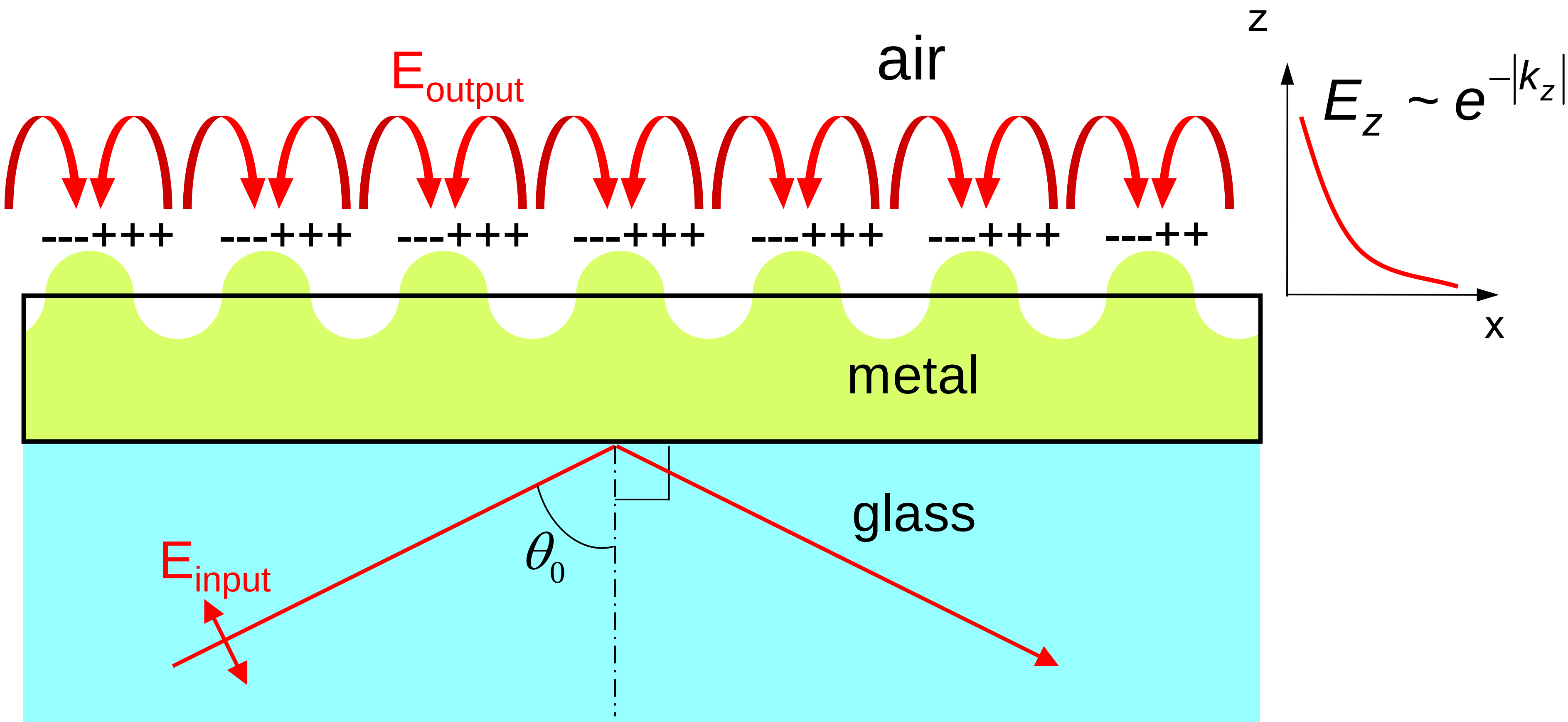
Imaging

Lithography

Strong field enhancement ⇒High S/N ratio

Shorter Wavelength ⇒Higher Resolution

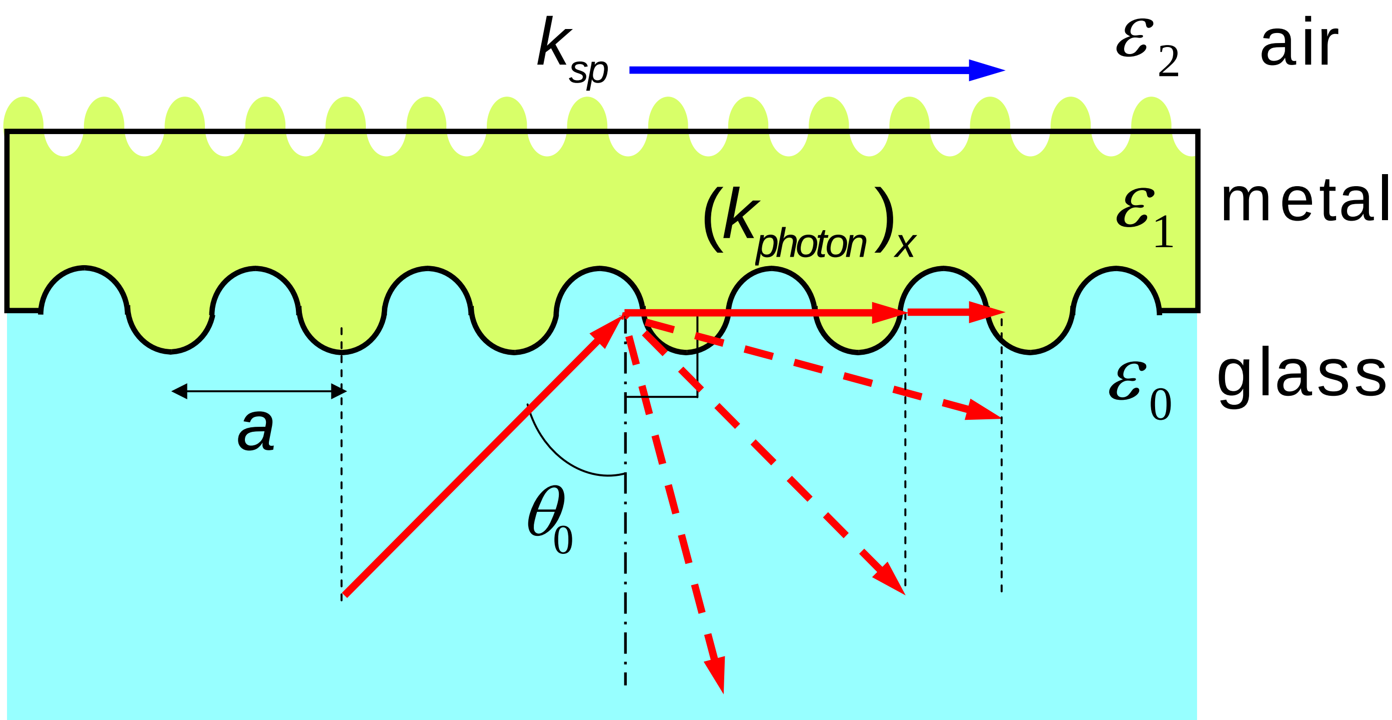
Field enhancement by SPR



$$\frac{E_{output}}{E_{input}} = 20 \sim 200!!$$

(Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*.1988, Berlin: Springer)

Higher resolution by SPR (I)



$$k_{sp} = (k_{photon})_x = \sqrt{\varepsilon_0}\frac{\omega}{c}\sin\theta_0 + mg \quad (g = 2\pi / a)$$

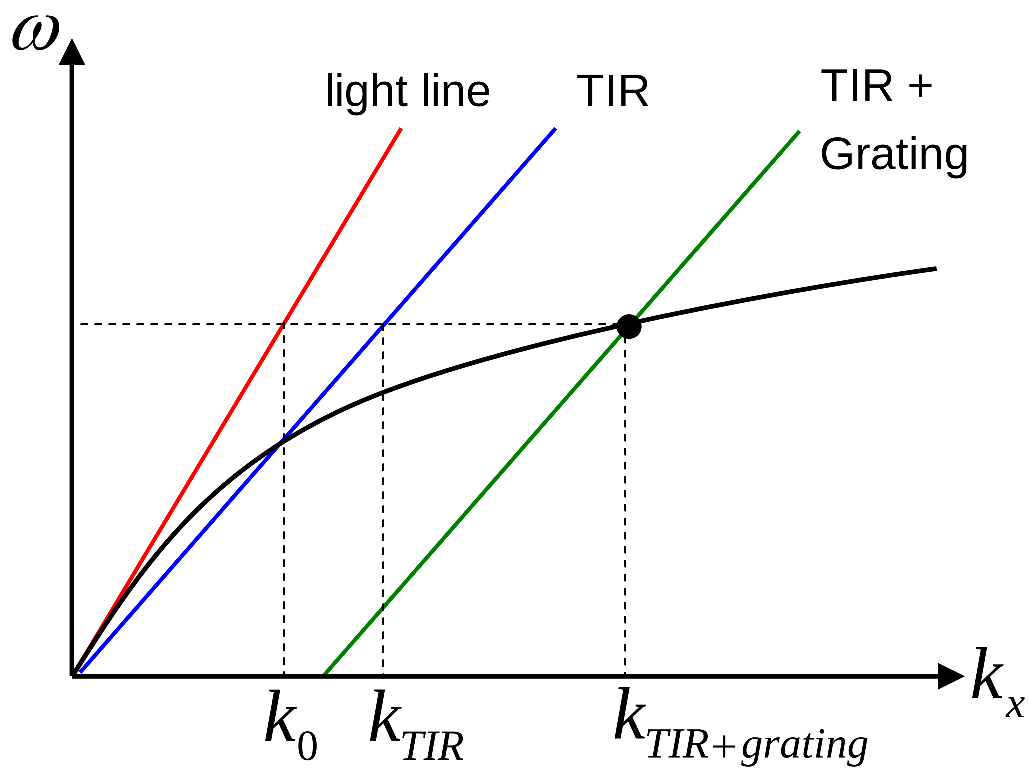
k: wavevector, a: grating period, m: diffraction order, ε: dielectric constant

Higher resolution by SPR (II)

$$E = \hbar\omega \quad (\hbar = h/2\pi)$$

$$p = \hbar k$$

$$\begin{cases} k_{surface\ plasmon} = \dfrac{\omega}{c}\left(\dfrac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2} \\ (k_{photon})_x = \sqrt{\varepsilon_0}\dfrac{\omega}{c}\sin\theta_0 + mg \end{cases}$$

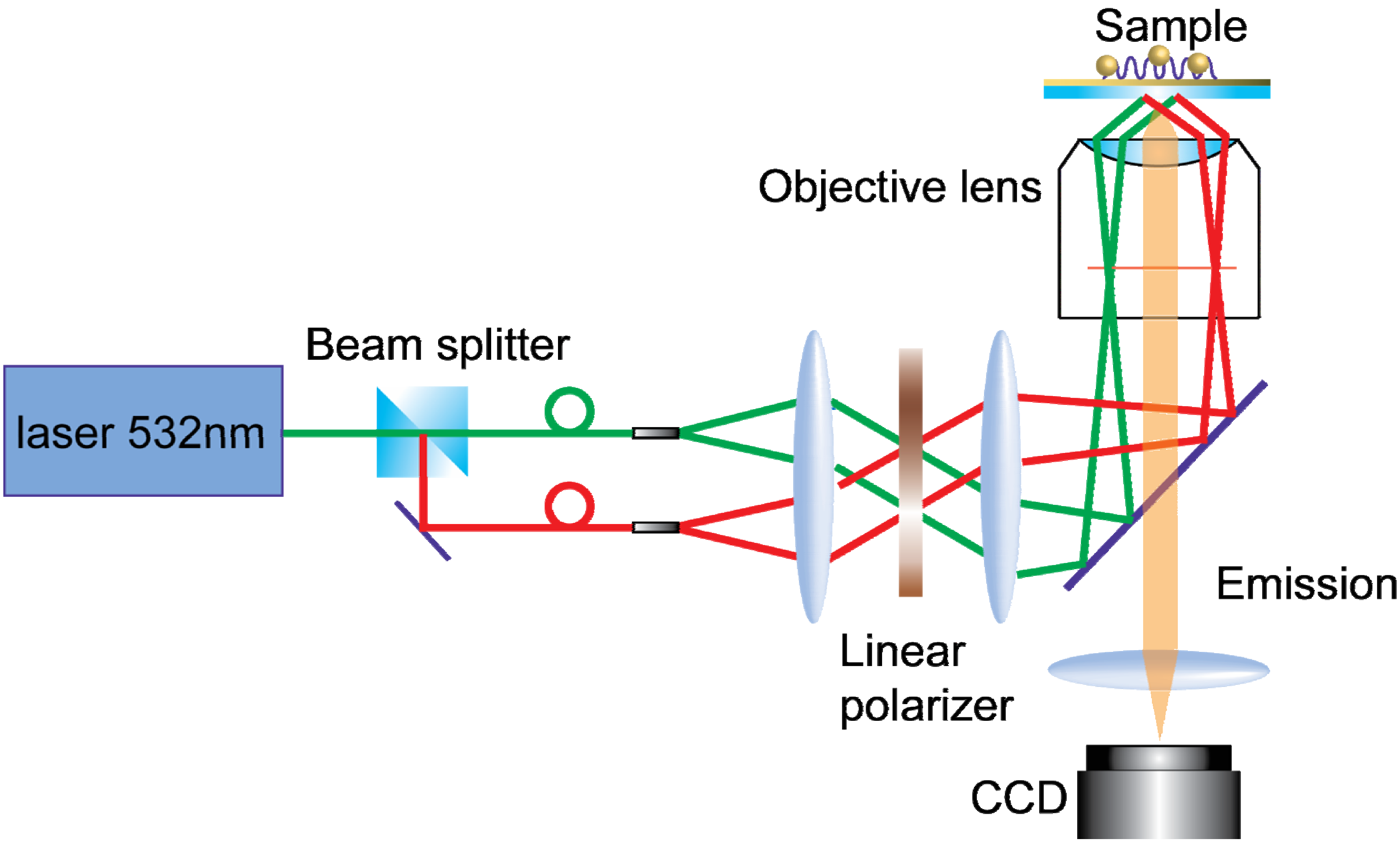


532 nm ➡ 104 nm !!

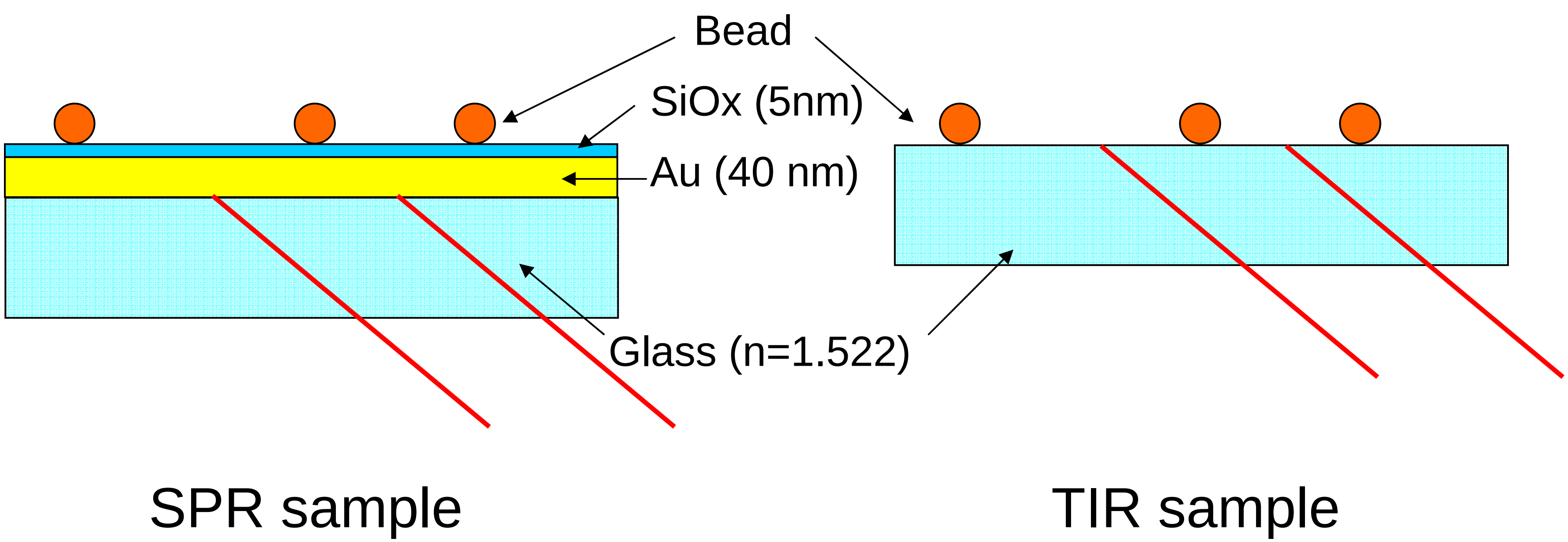
k: wavevector, a: grating period, m: diffraction order, ε: dielectric constant

(Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*. 1988, Berlin: Springer)

Experimental setup

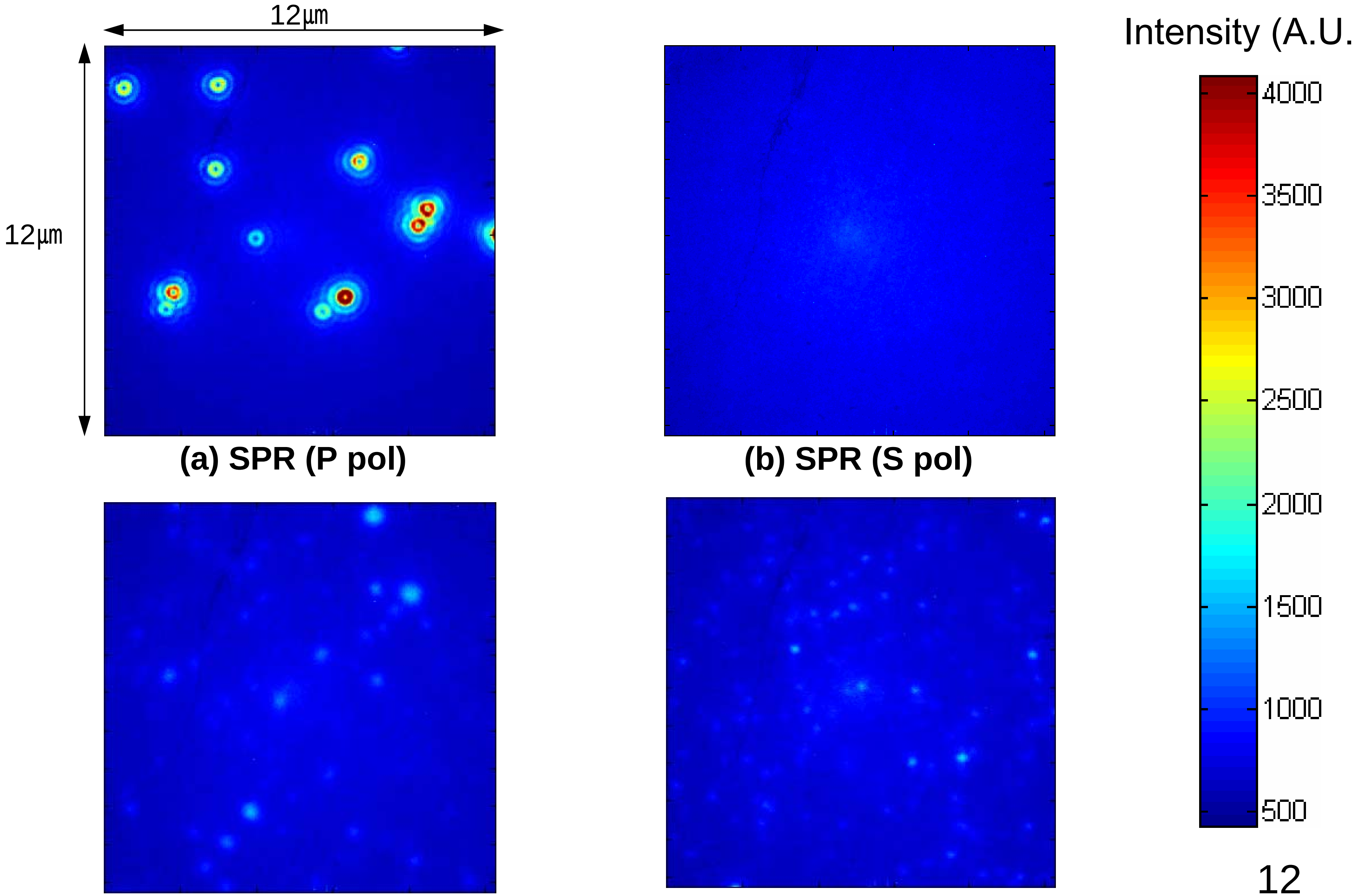


SPR field enhancement experiment (I)



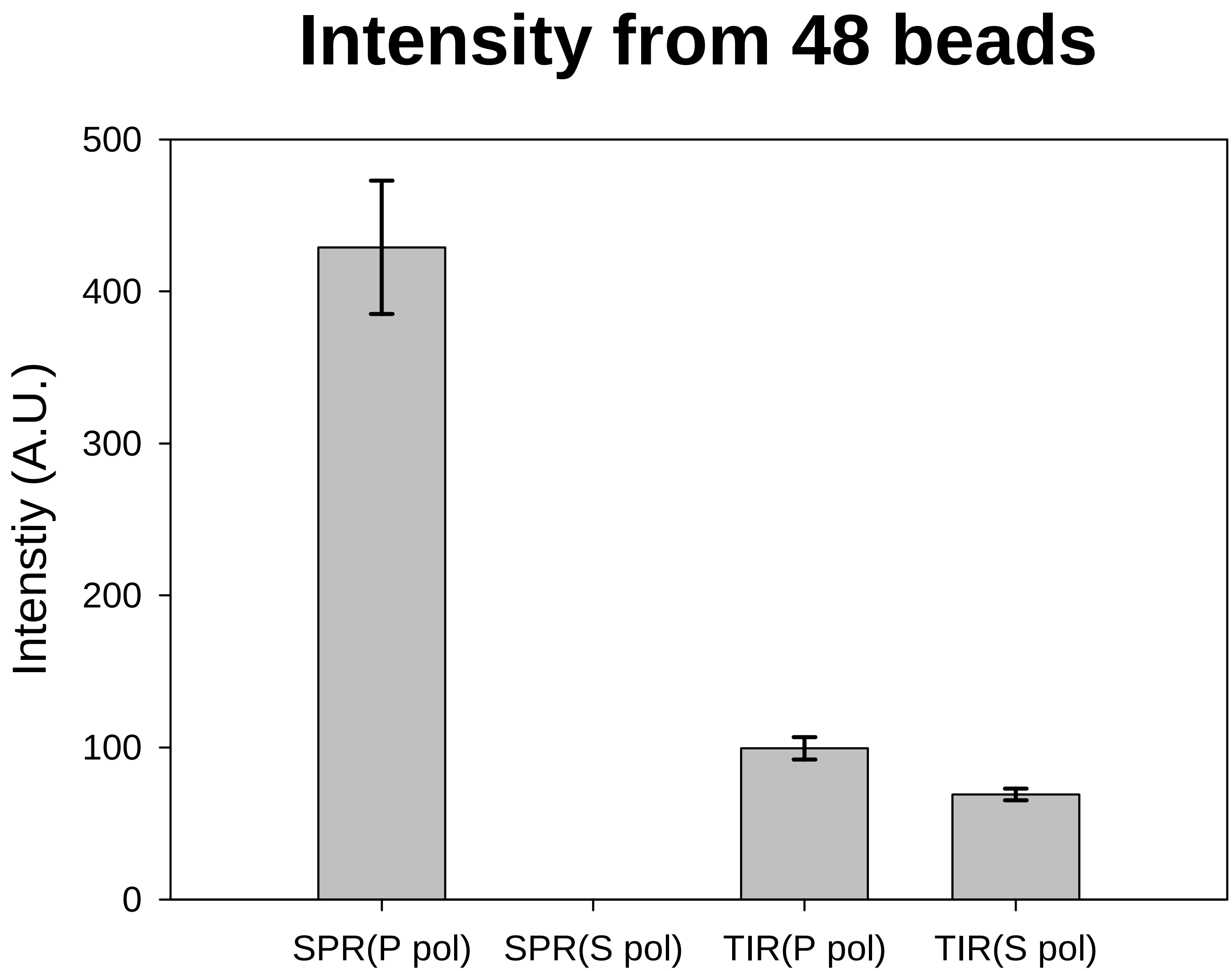
- ➢Fluorescent beads (d = 40nm)
- ➢SPR angle (~45°)
- ➢Incident power (7.8 mW)
- ➢N = 48 samples

SPR field enhancement experiment (II)



(a) SPR (P pol)
(b) SPR (S pol)
(c) TIR (P pol)
(d) TIR (S pol)

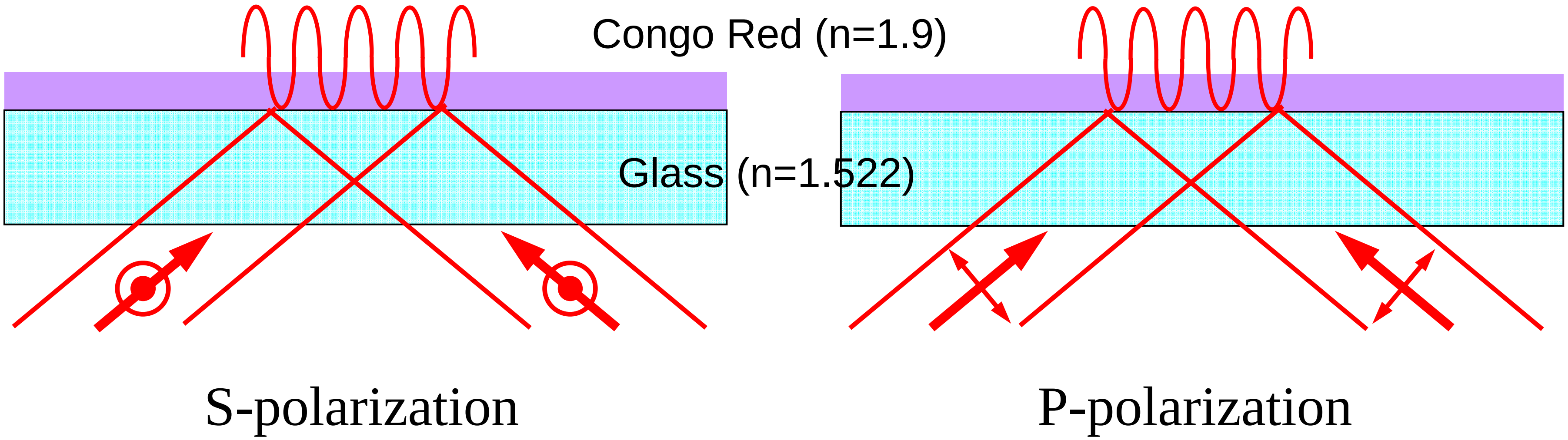
SPR field enhancement experiment (III)



P-value<0.001

TIR Lithography experiment (I)

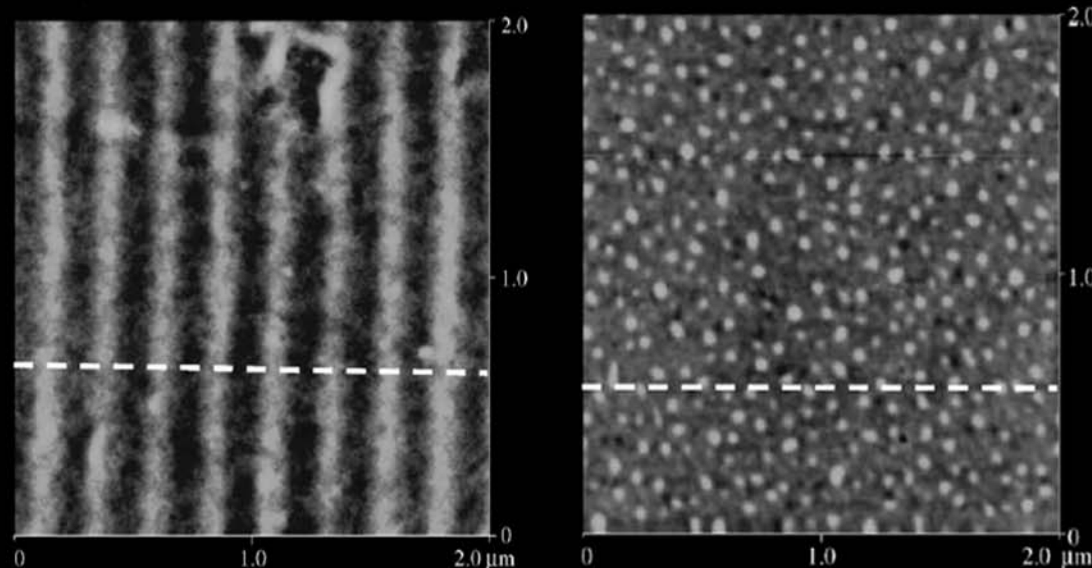
(Ohdaira, Y., et al., Colloids Surf. A, 2006)



- ➢Spin coating Congo Red solution with deionized water
- ➢Exposure (800 mW/cm^2 S-polarization for 30 min)
- ➢Exposure (2000 mW/cm^2 P-polarization for 10 min)

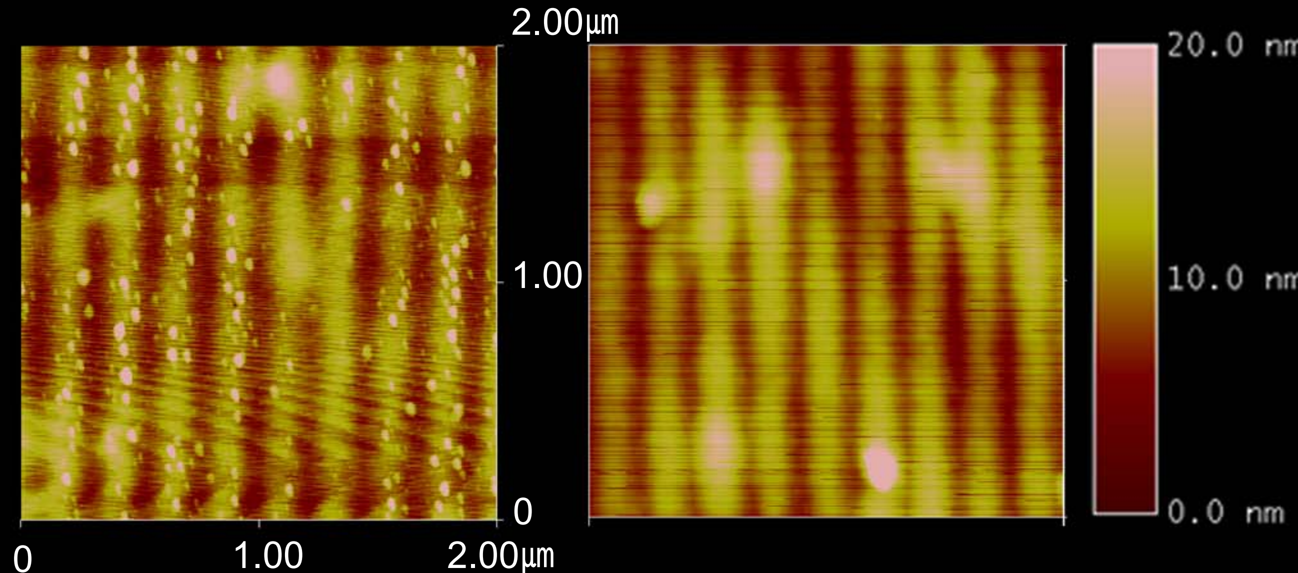
TIR Lithography experiment (II)

(Ohdaira, Y., et al.,
Colloids Surf. A, 2006)



(a) S-polarization (b) P-polarization

(Kim, Y., et al.,
In preparation)



Summary

Interference of two surface plasmon waves for imaging and lithography.

1) Strong field enhancement (high S/N ratio)

2) Longer wave vector (higher resolution)

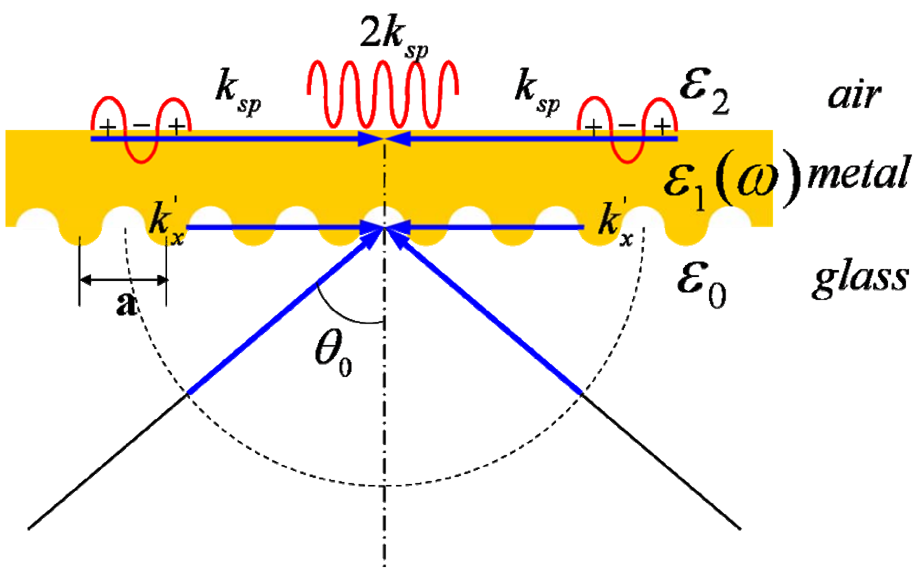
The results:

1) SPR strong field enhancement (bead imaging)

2) P-polarization Congo Red lithography is possible.

Future Work

- Make a corrugated gold coated glass sample
- The high resolution (~50 nm) imaging and lithography with the sample

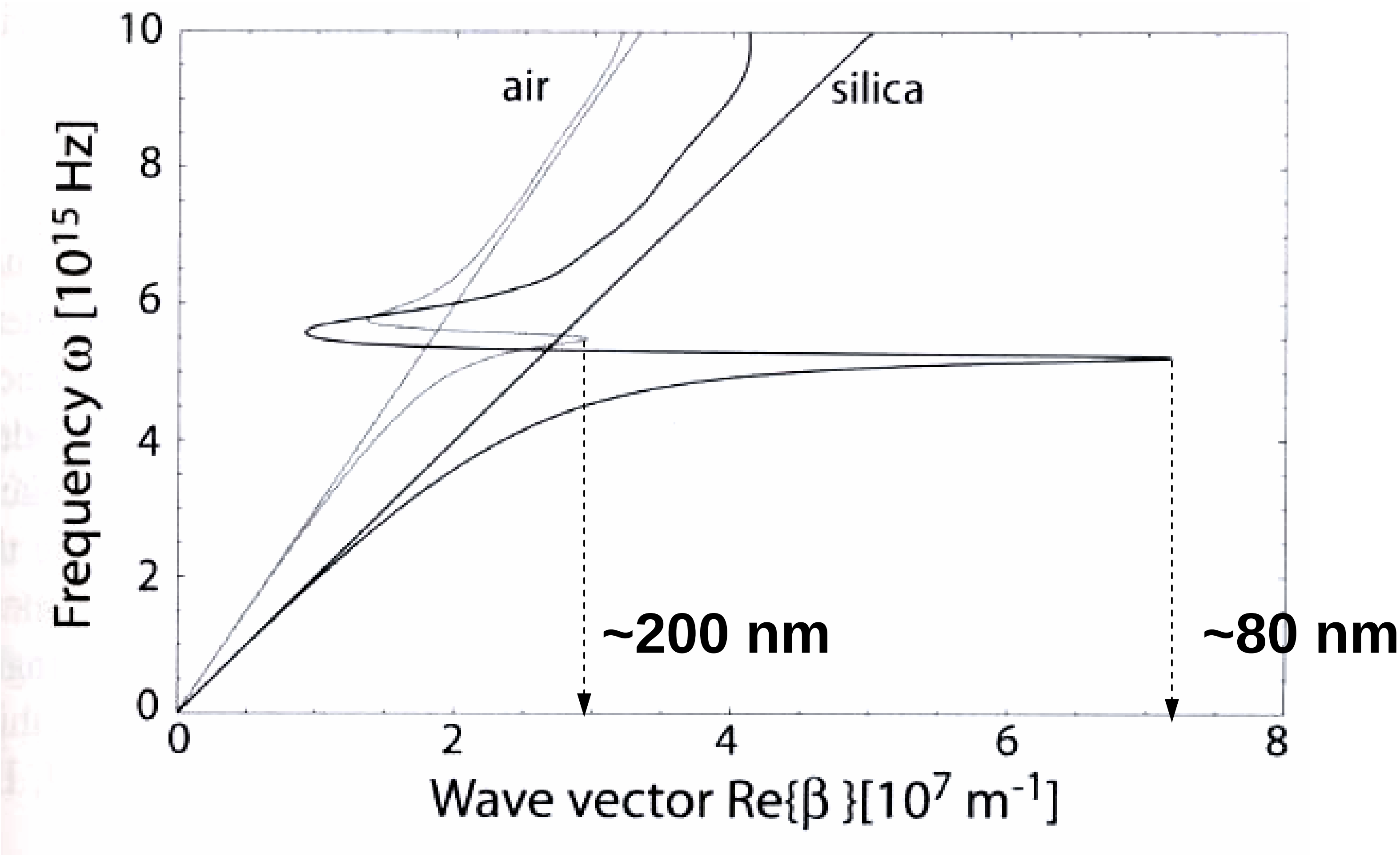


Thank you !

&

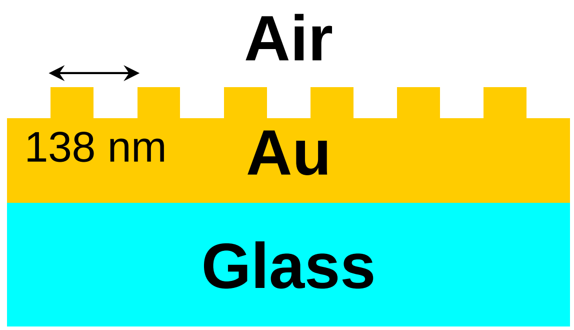
Questions ?

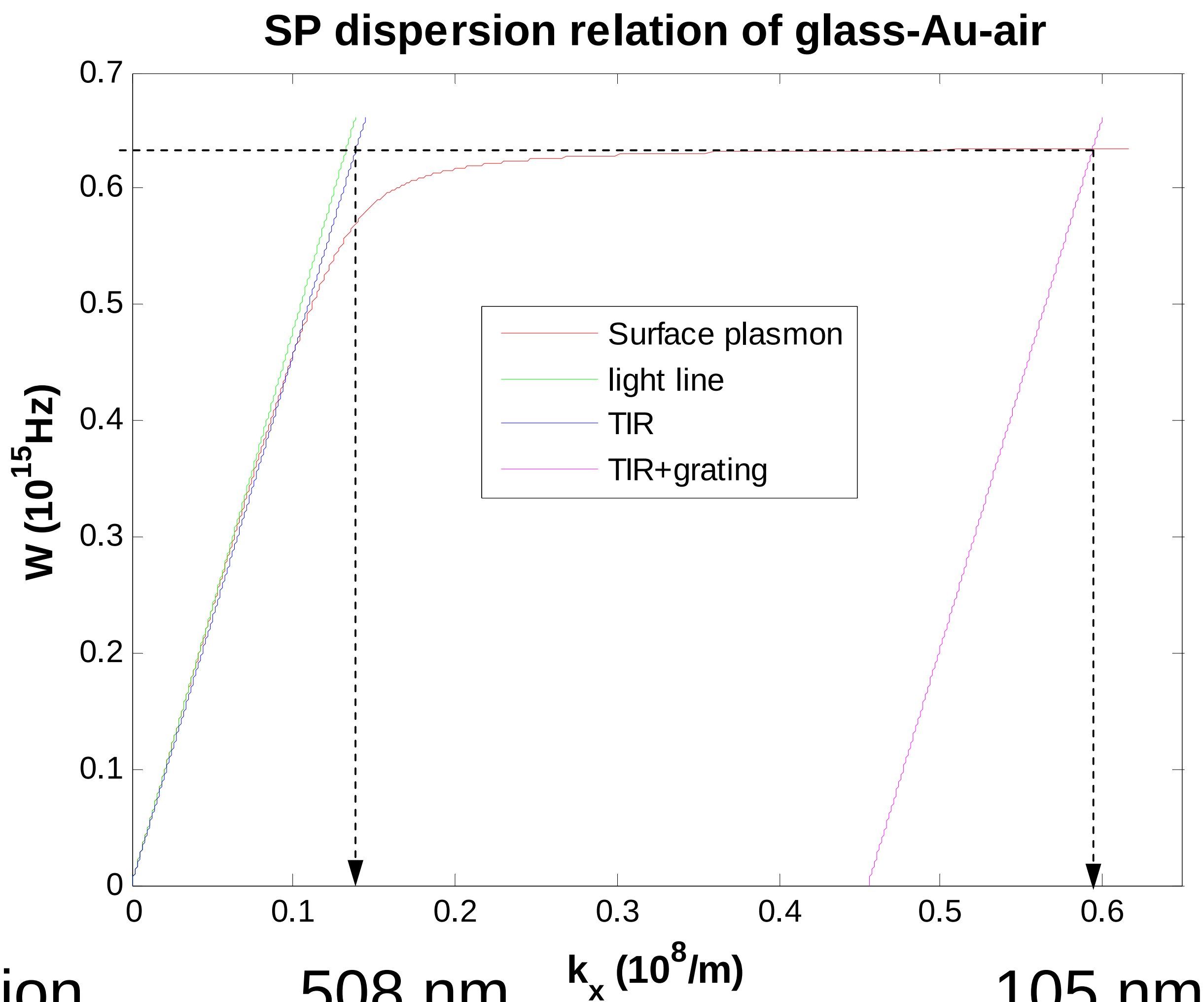
Future Work (II)



(Maier, *Plasmonics: Fundamentals and Applications*. 2007, Springer)

Future Work (II)



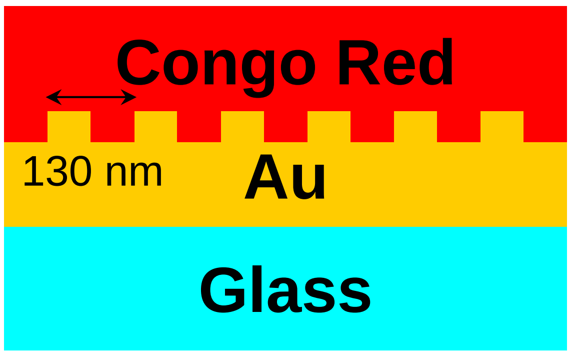


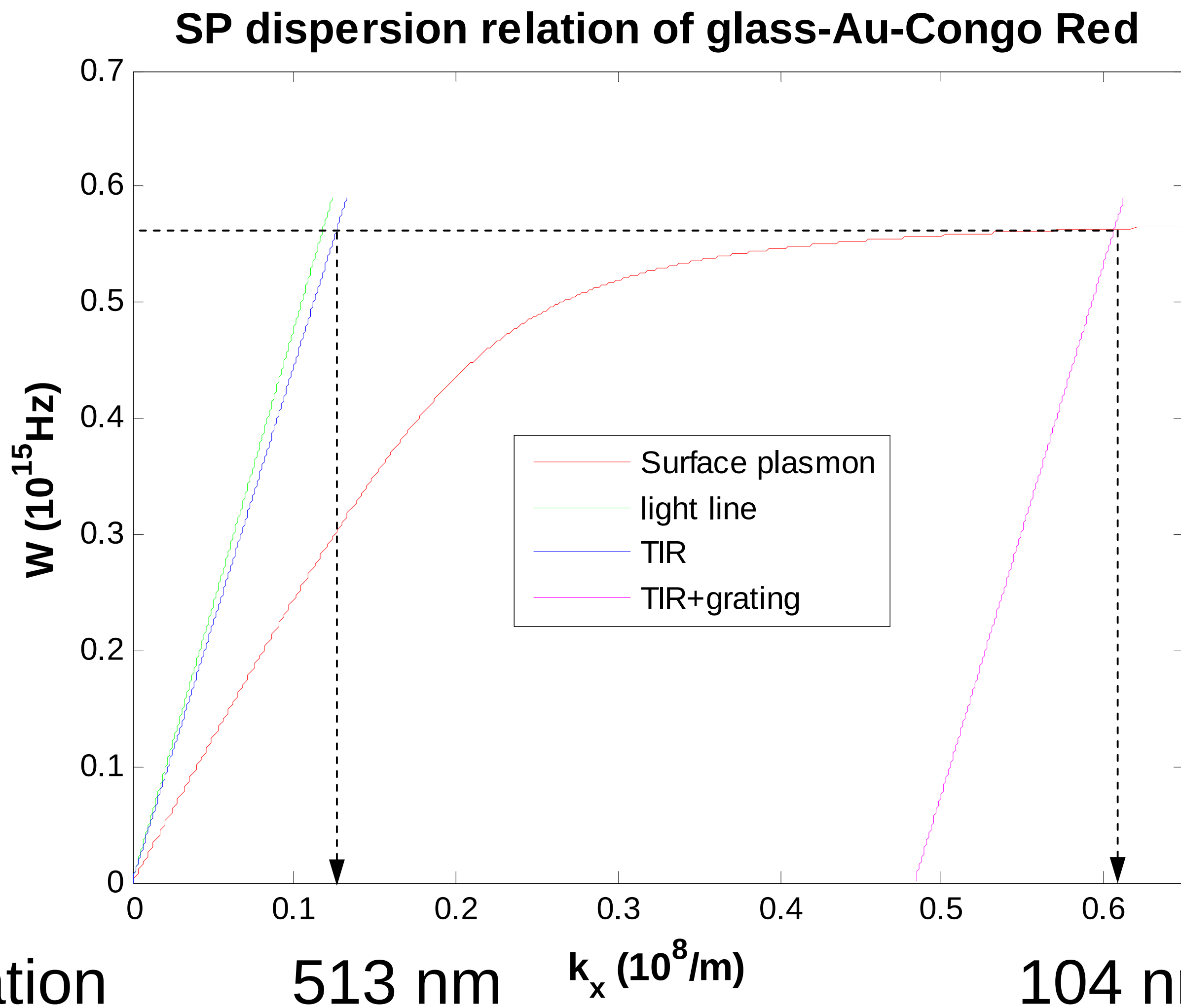
473 nm excitation

508 nm

105 nm

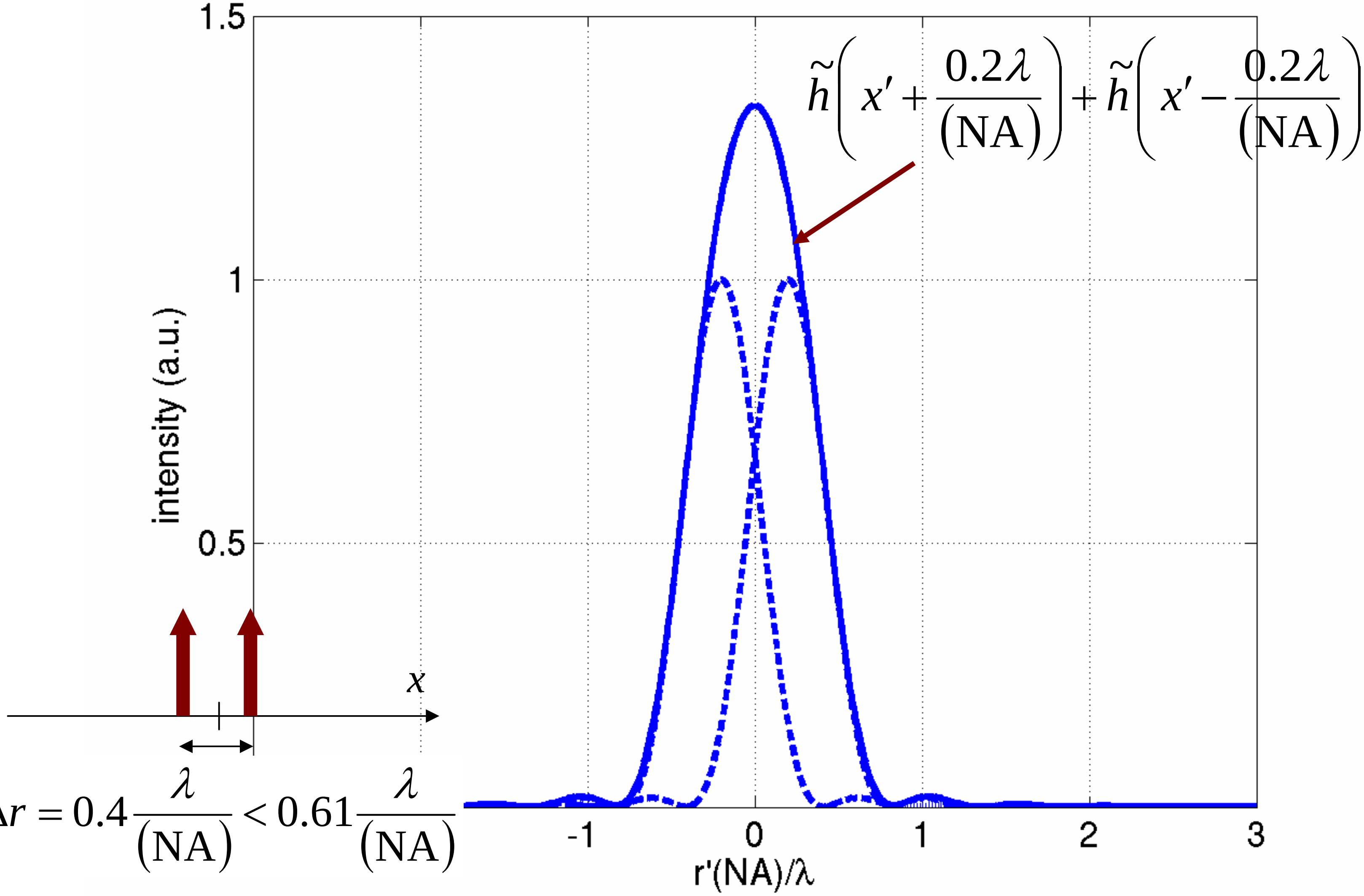
Future Work (II)





532 nm excitation 513 nm 104 nm

Resolution I



$$\Delta r = 0.4\frac{\lambda}{(\mathrm{NA})} < 0.61\frac{\lambda}{(\mathrm{NA})}$$

(MIT 2.710 Optics lecture note)

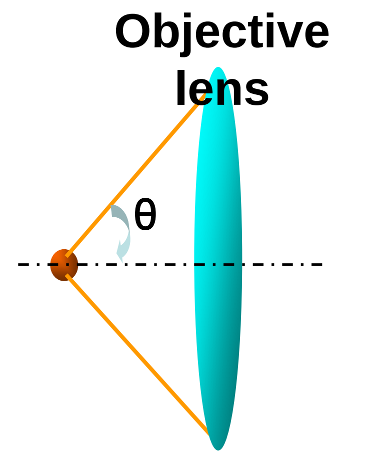
Resolution II

- Rayleigh resolution criterion (imaging)

$$0.61\frac{\lambda}{NA} = 0.61\frac{\lambda}{n\sin\theta}$$

- Optical Projection Lithography resolution

$$\kappa_1\frac{\lambda}{NA} = \kappa_1\frac{\lambda}{n\sin\theta}$$

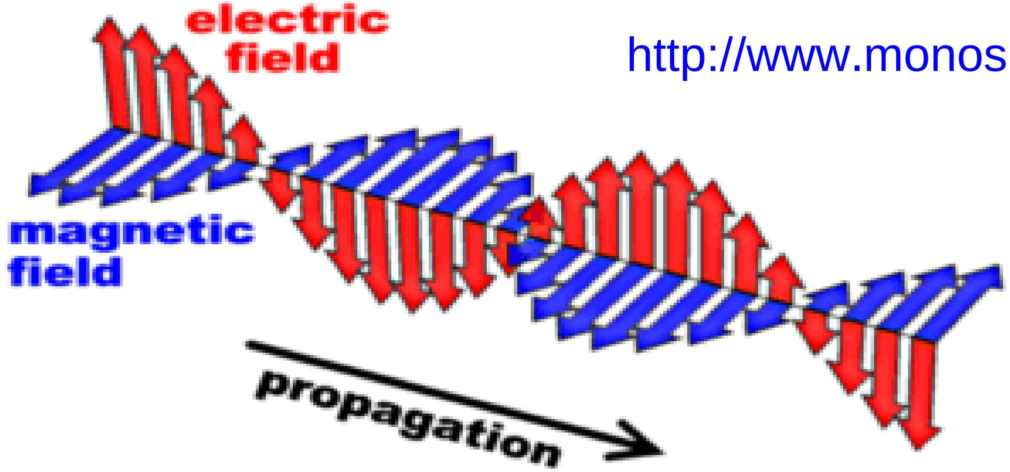


Numerical Aperture
NA= ***n*** **sin θ**

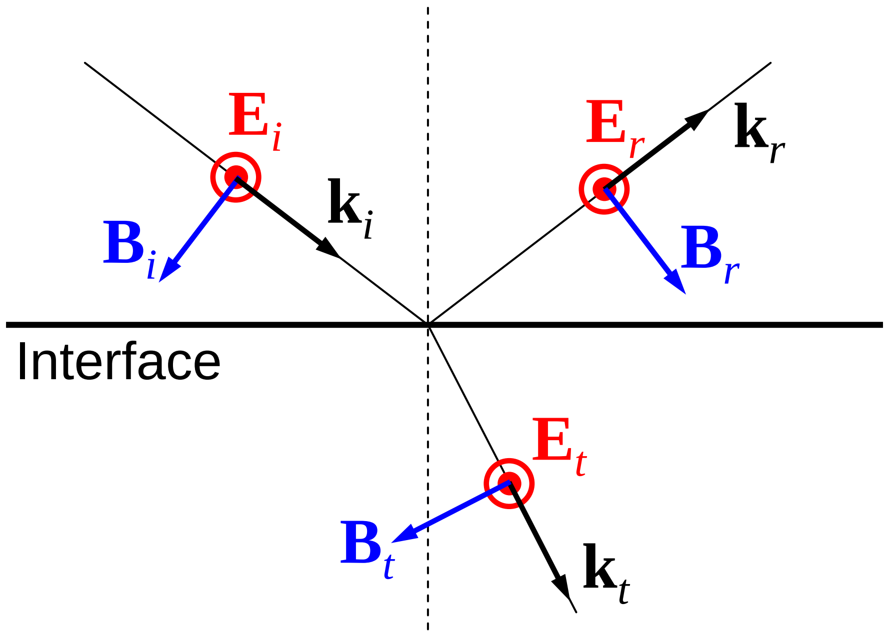
K1: constant for a specific lithographic process

(Chiu at al., IBM Journal of Research and Development, 1997. 41)

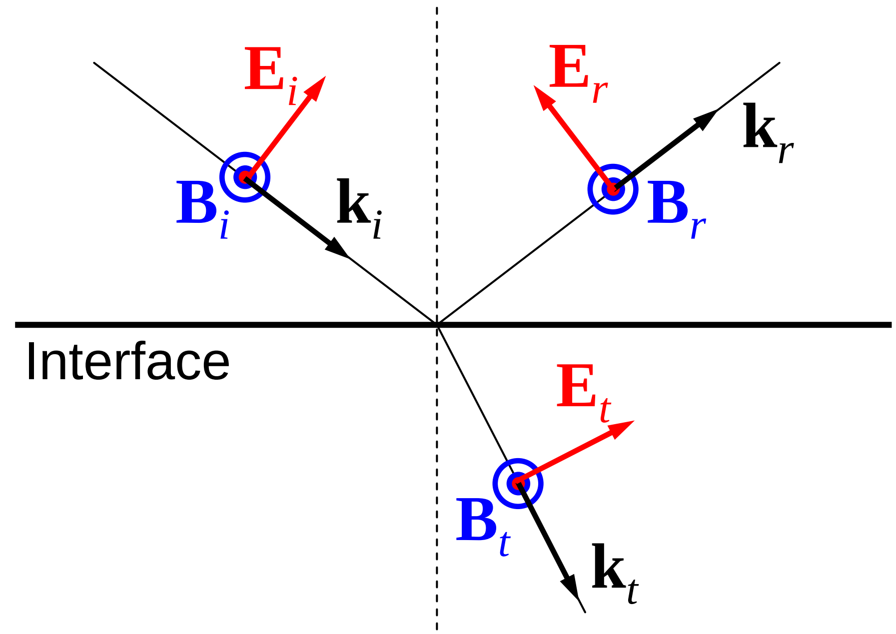
Polarization



http://www.monos.leidenuniv.nl/smo

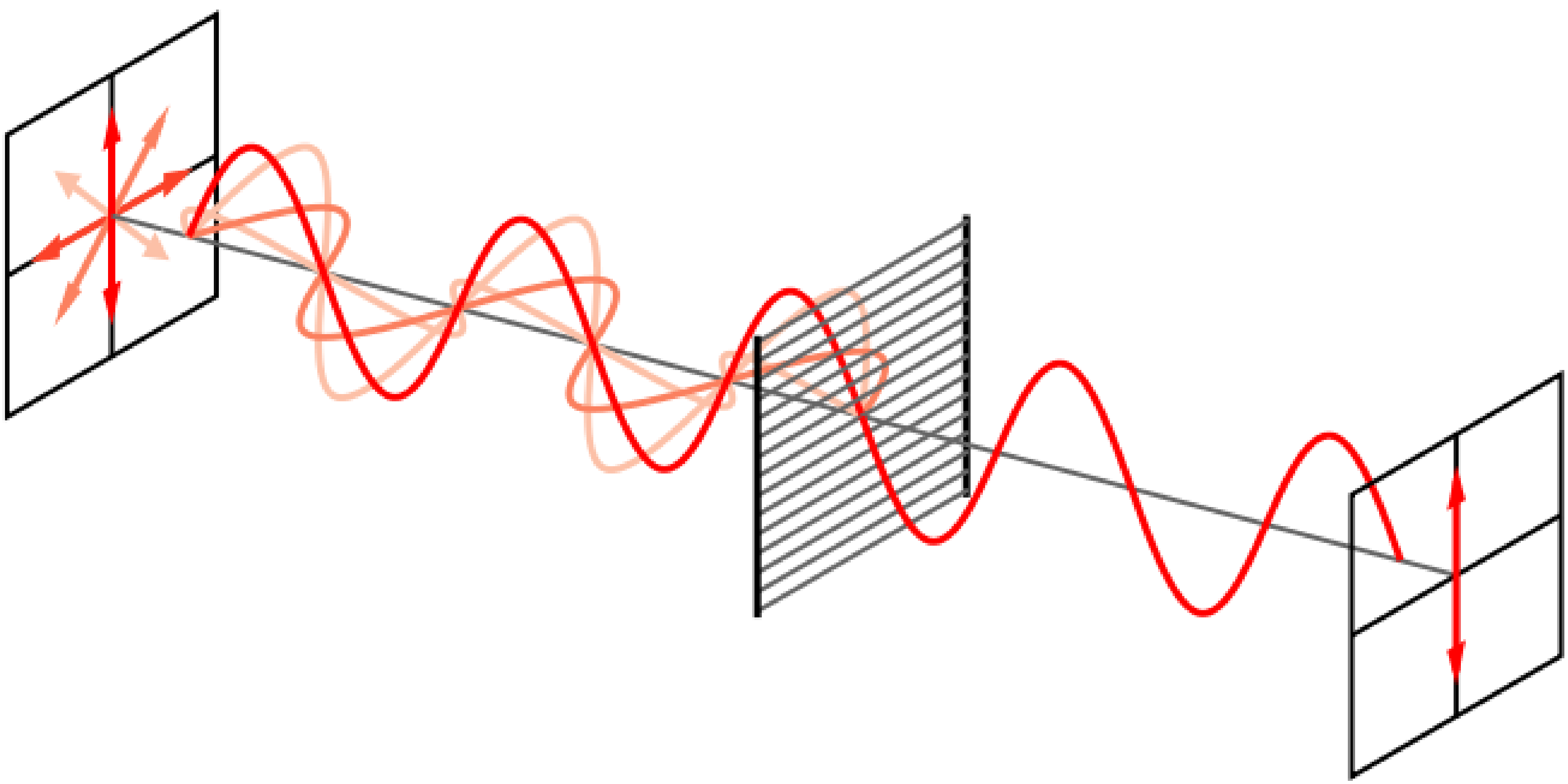


S-polarization



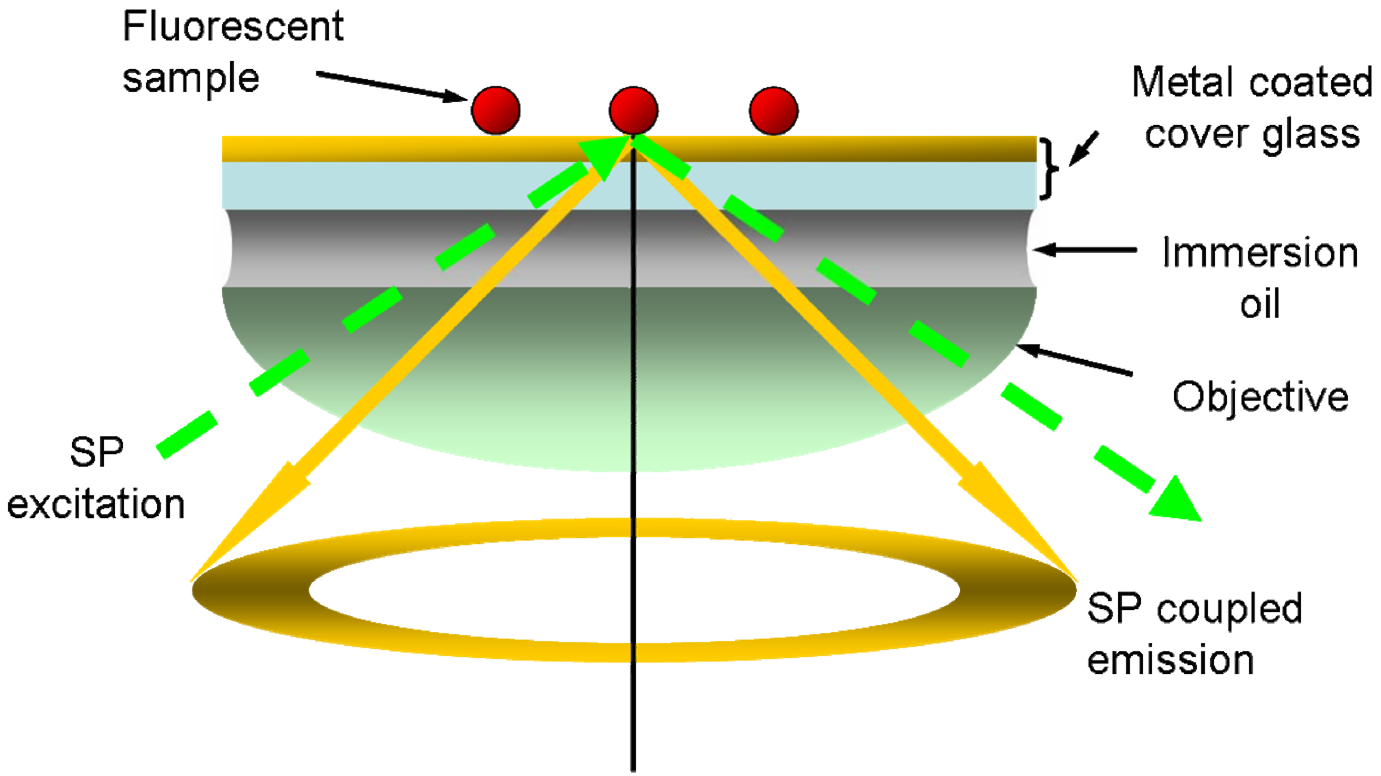
P-polarization

Linear polarizer



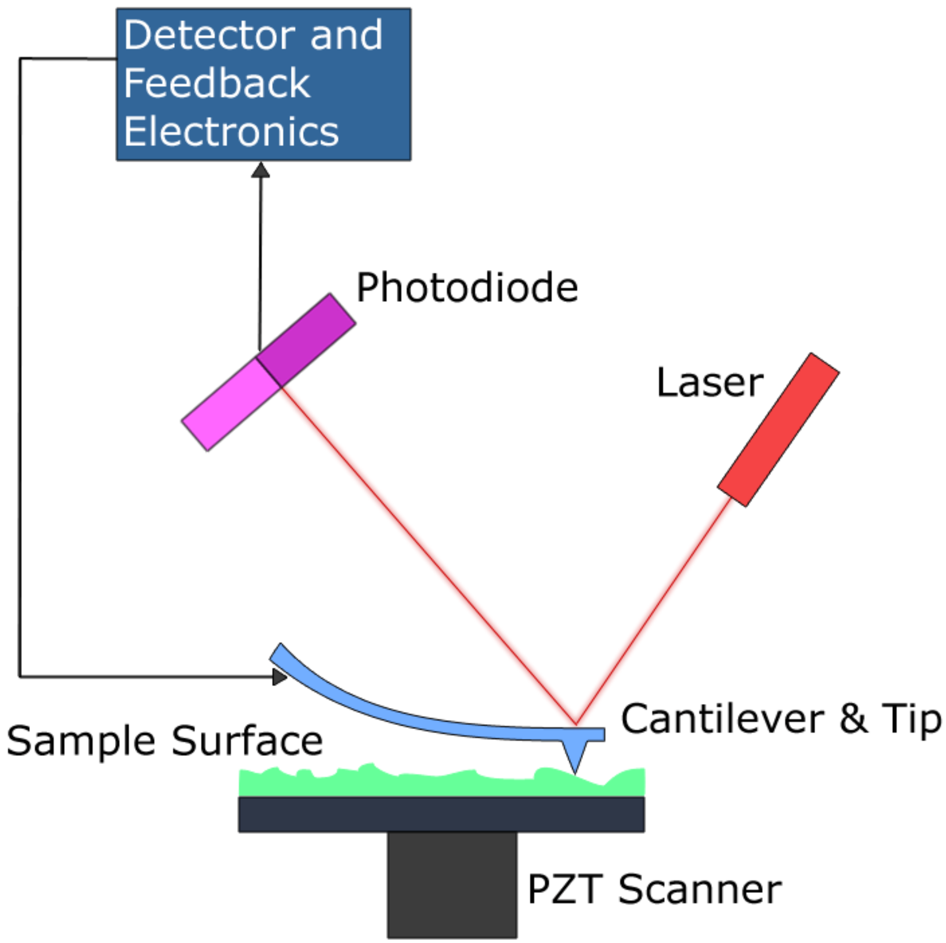
(Collett, Edward. Field Guide to Polarization, SPIE Field Guides vol. FG05, SPIE (2005))

Surface Plasmon-Coupled Emission



(E. Chung, thesis, MIT, 2007)

AFM

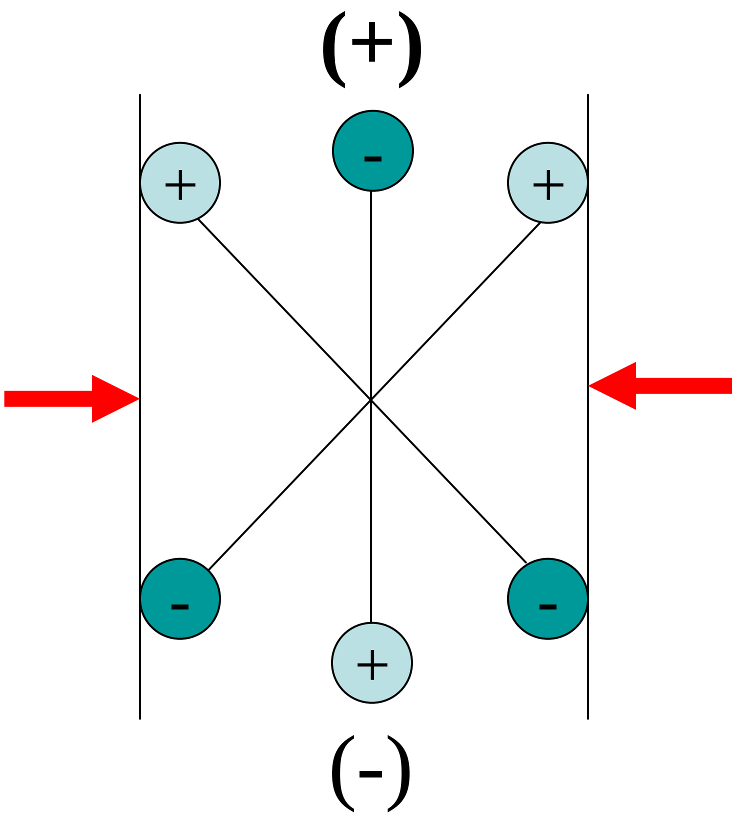


- Deflection of the cantilever is measured.
- Feedback mechanism prevent the collision of the tip and the surface.

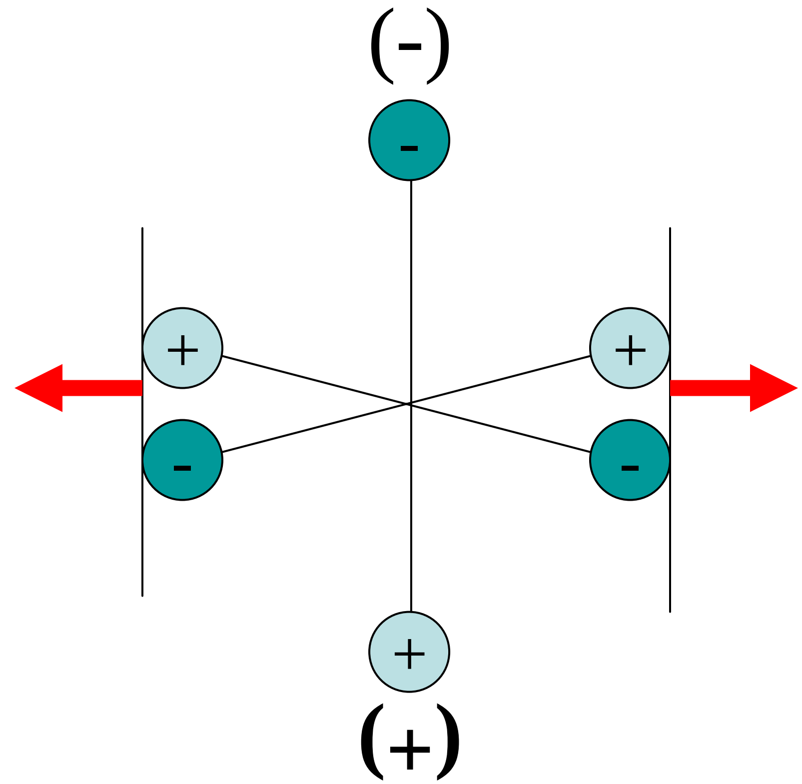
Humphris at al., A mechanical microscope: High-speed atomic force microscopy, Applied Physics Letters 86, 034106 (2005).

Piezoelectric effect

The unit cell of crystal silicon dioxide deformation



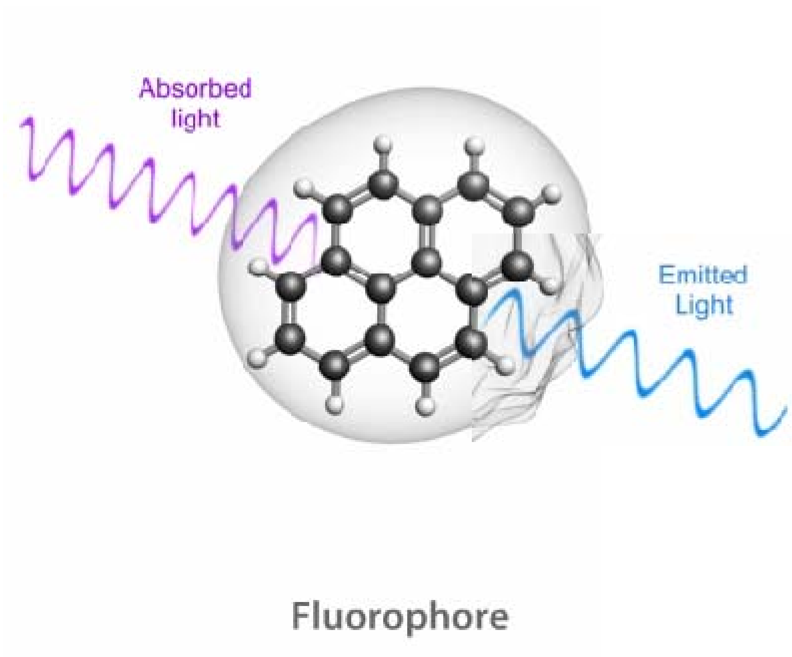
A pushing force:
(aka: compression)

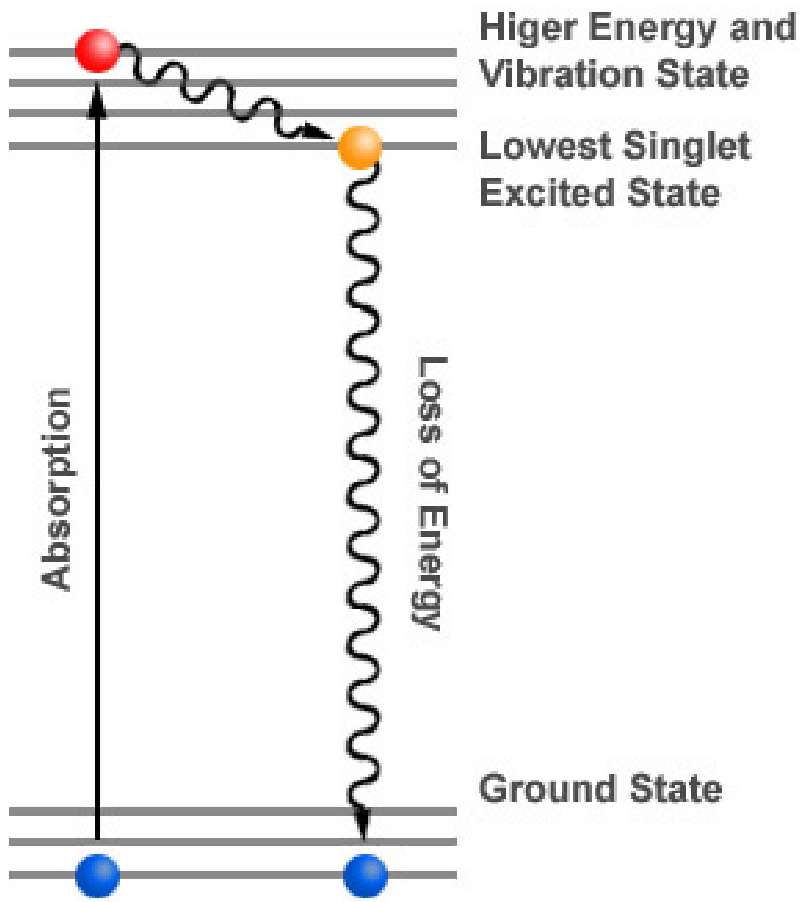


A pulling force:
(aka: tension)

(http://www.ndt-ed.org/)

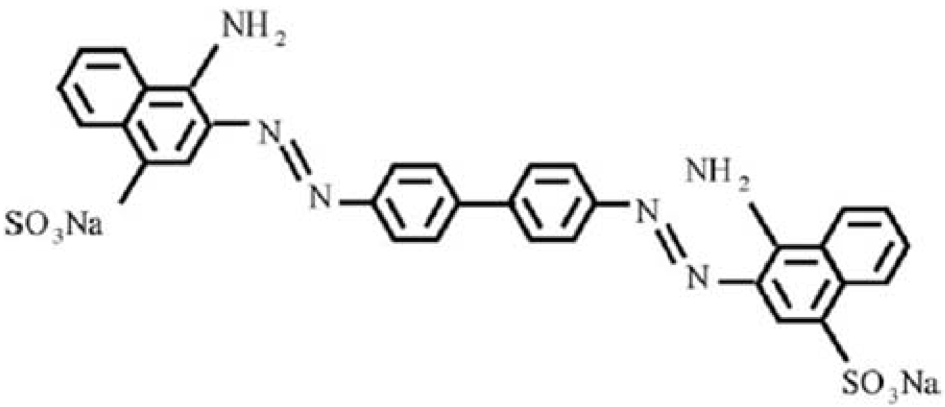
Fluorescence

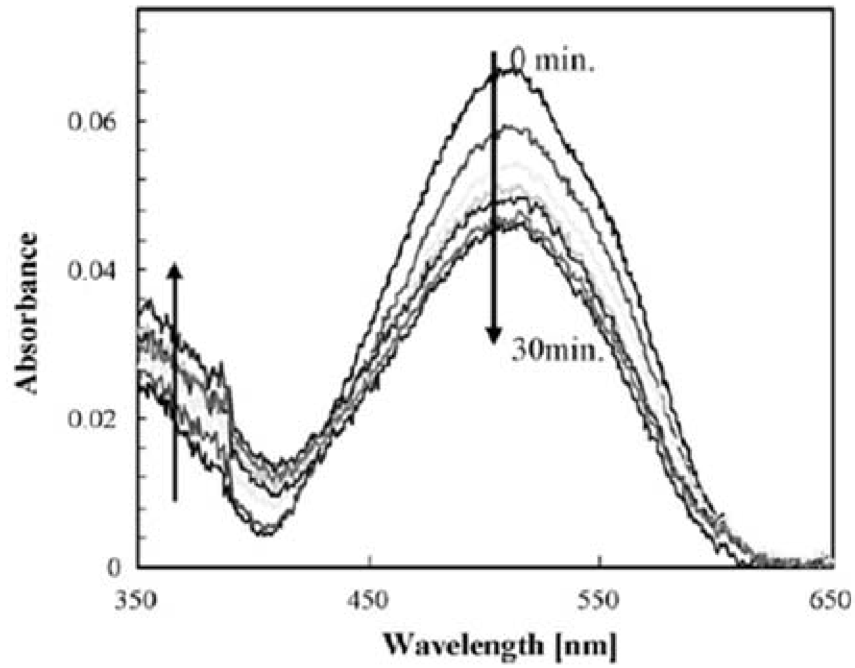


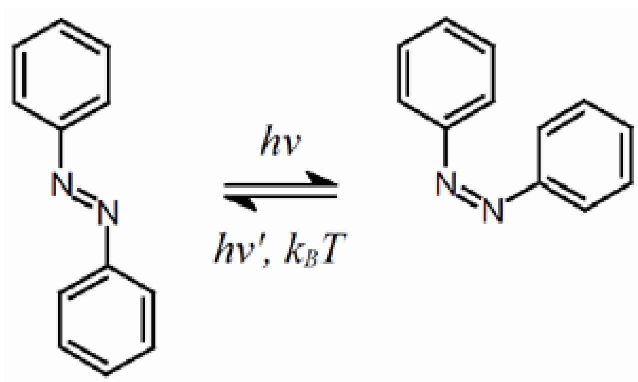


(http://www.probes.com/)

Congo Red



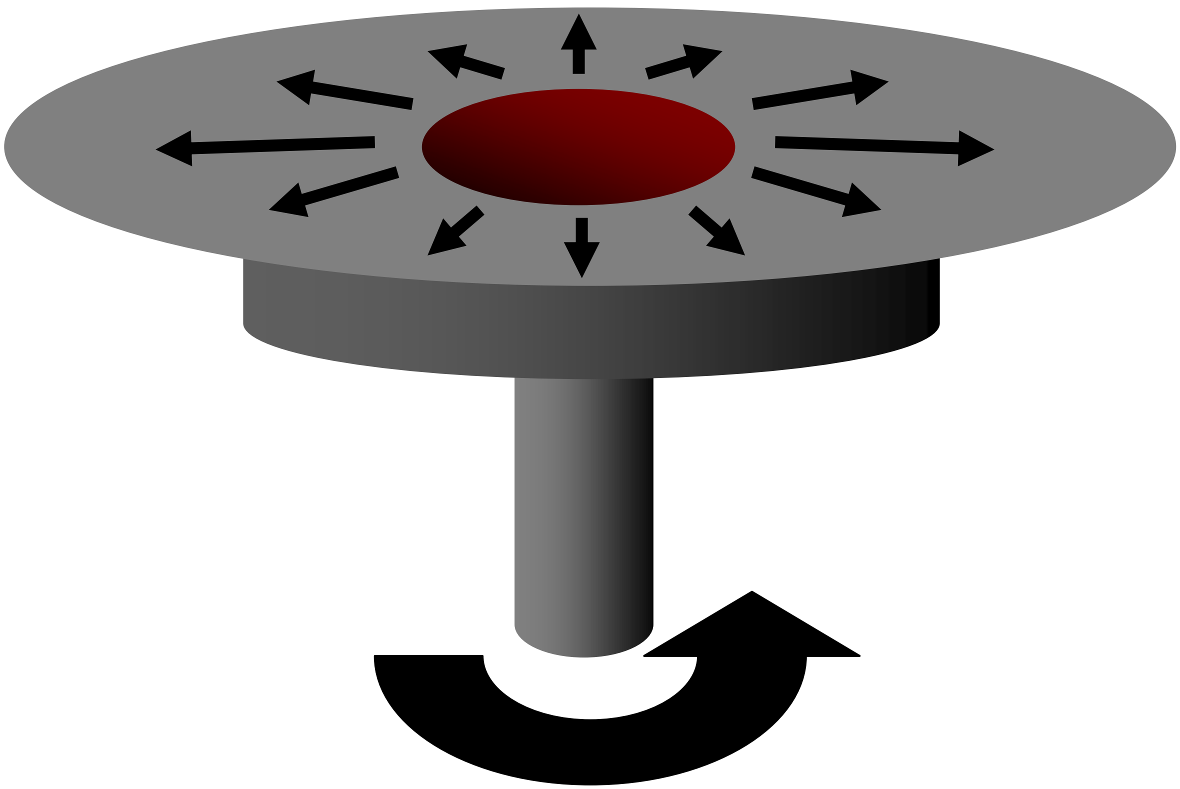




(Ohdaira, Y., et al., Colloids Surf. A, 2006)
(http://en.wikipedia.org/wiki/Azobenzene)

Spin coating

Centrifugal force spread a fluid resin.

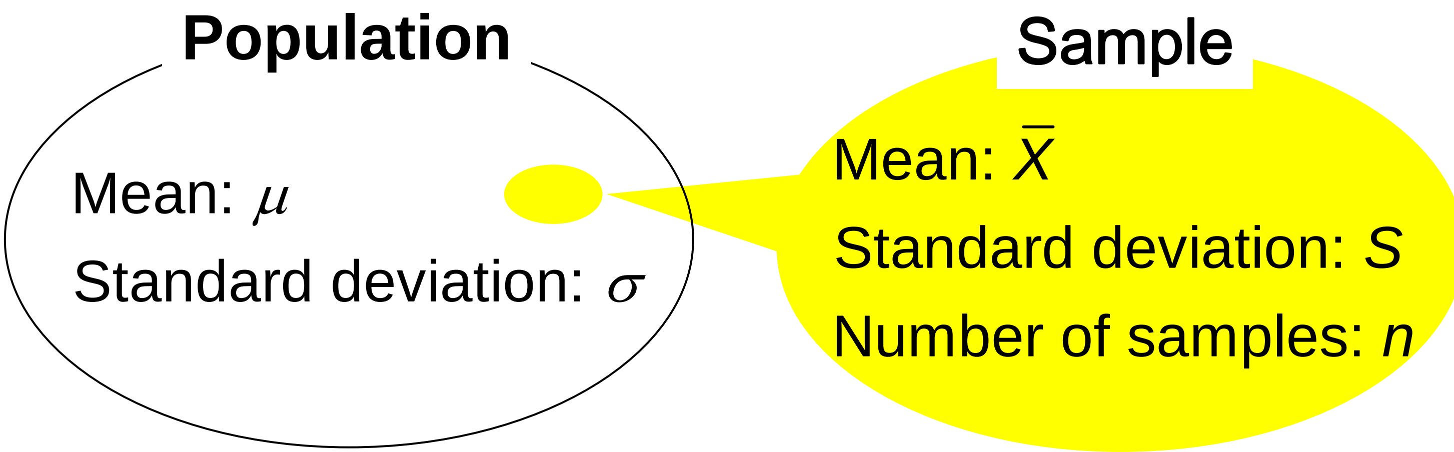


CCD & CMOS

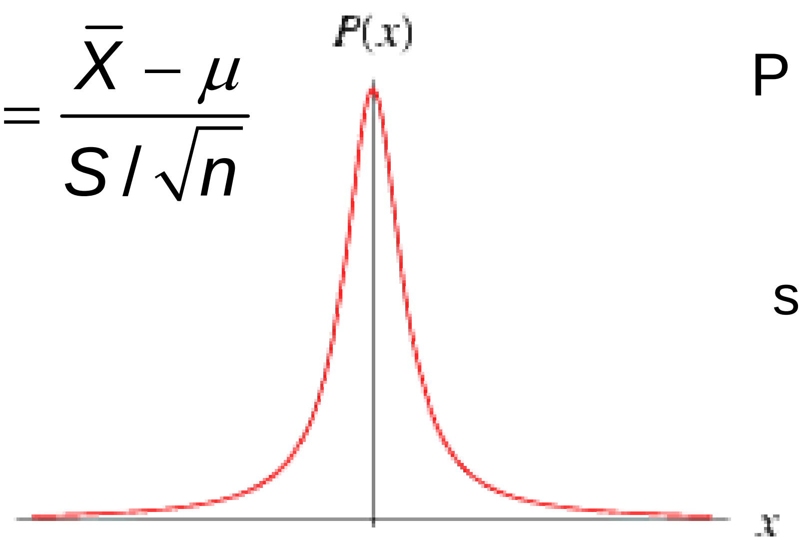
photon to electron

CCD	CMOS
Uniform image quality	Cost less
High fill factor	Consume less power
Low noise	Many function
Simple	Integration on one chip

t-test



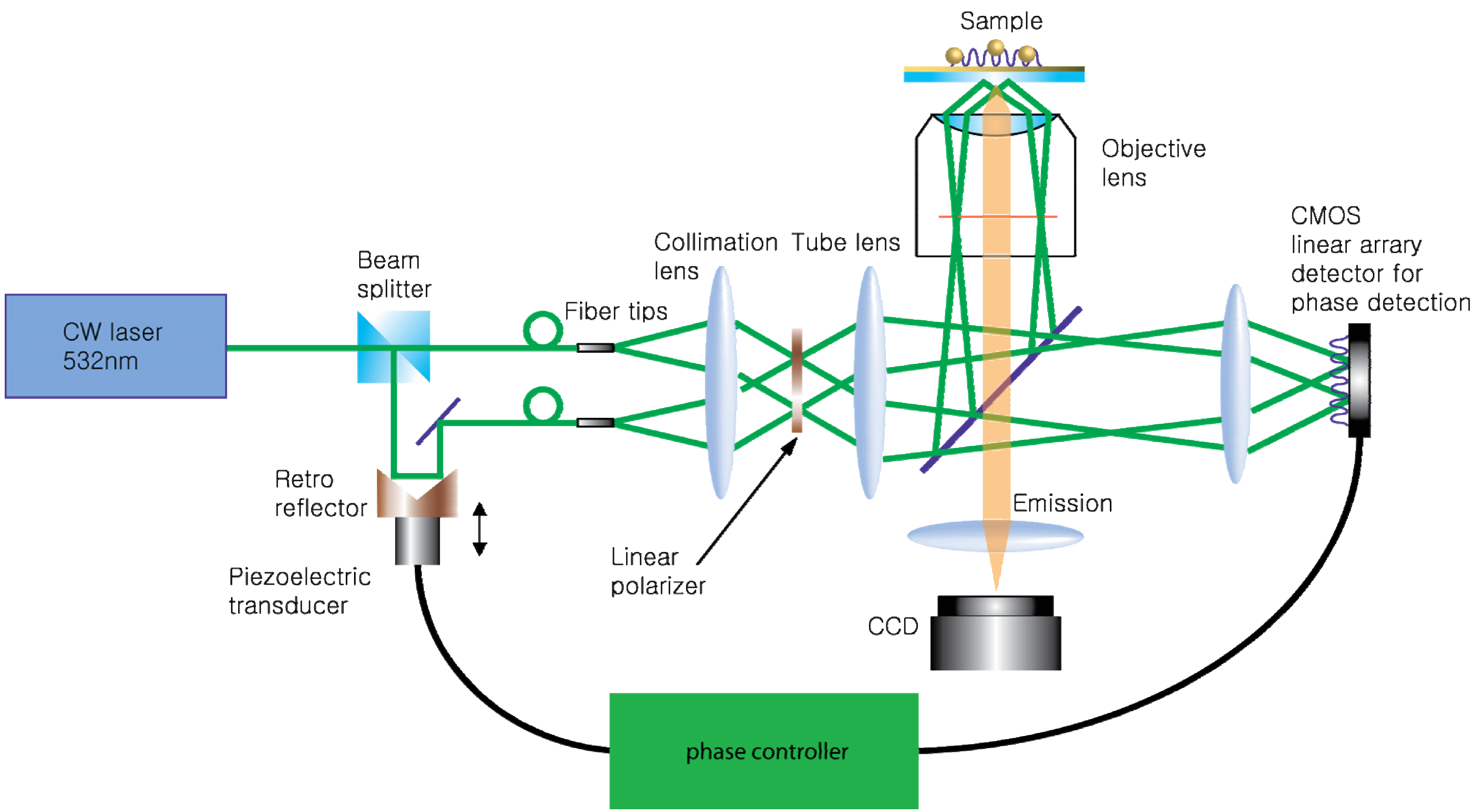
$$T = \frac{\bar{X} - \mu}{S / \sqrt{n}}$$



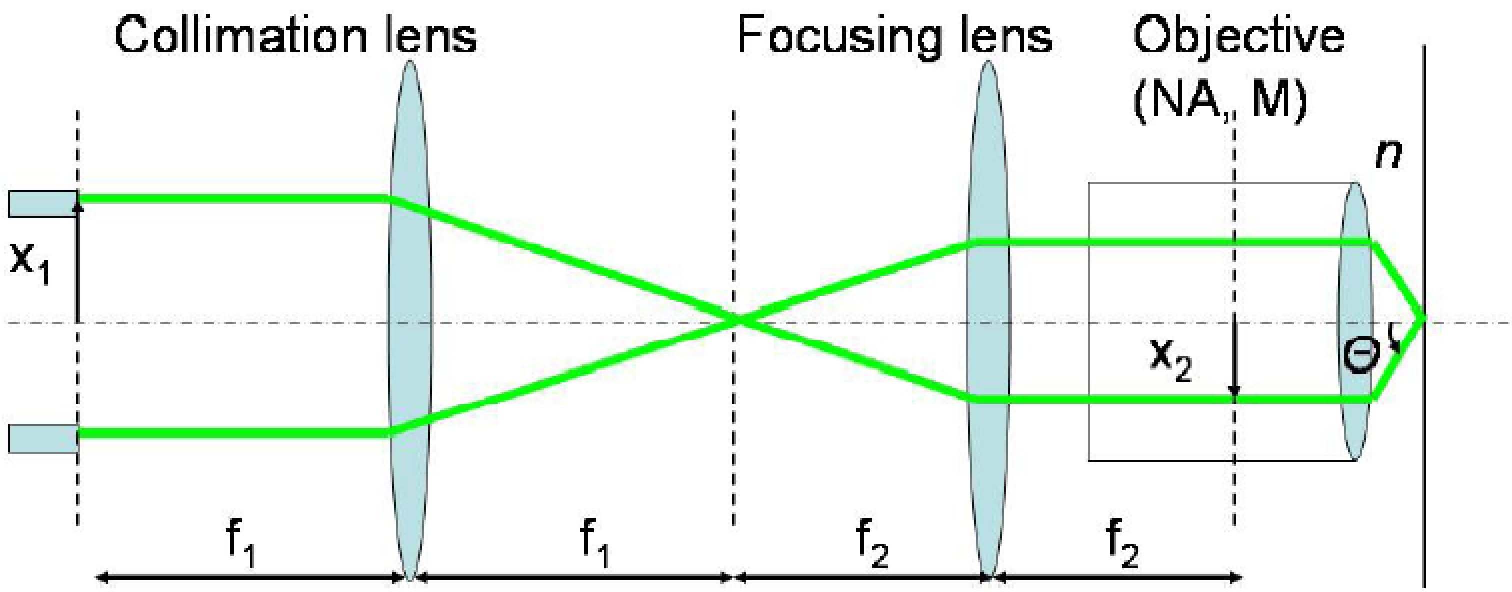
P value : the provability that $\bar{X} \neq \mu$ when random sampling

small P value : we can trust $\bar{X}$ as μ with higher probability.

Original experimental setup



Fringe spacing

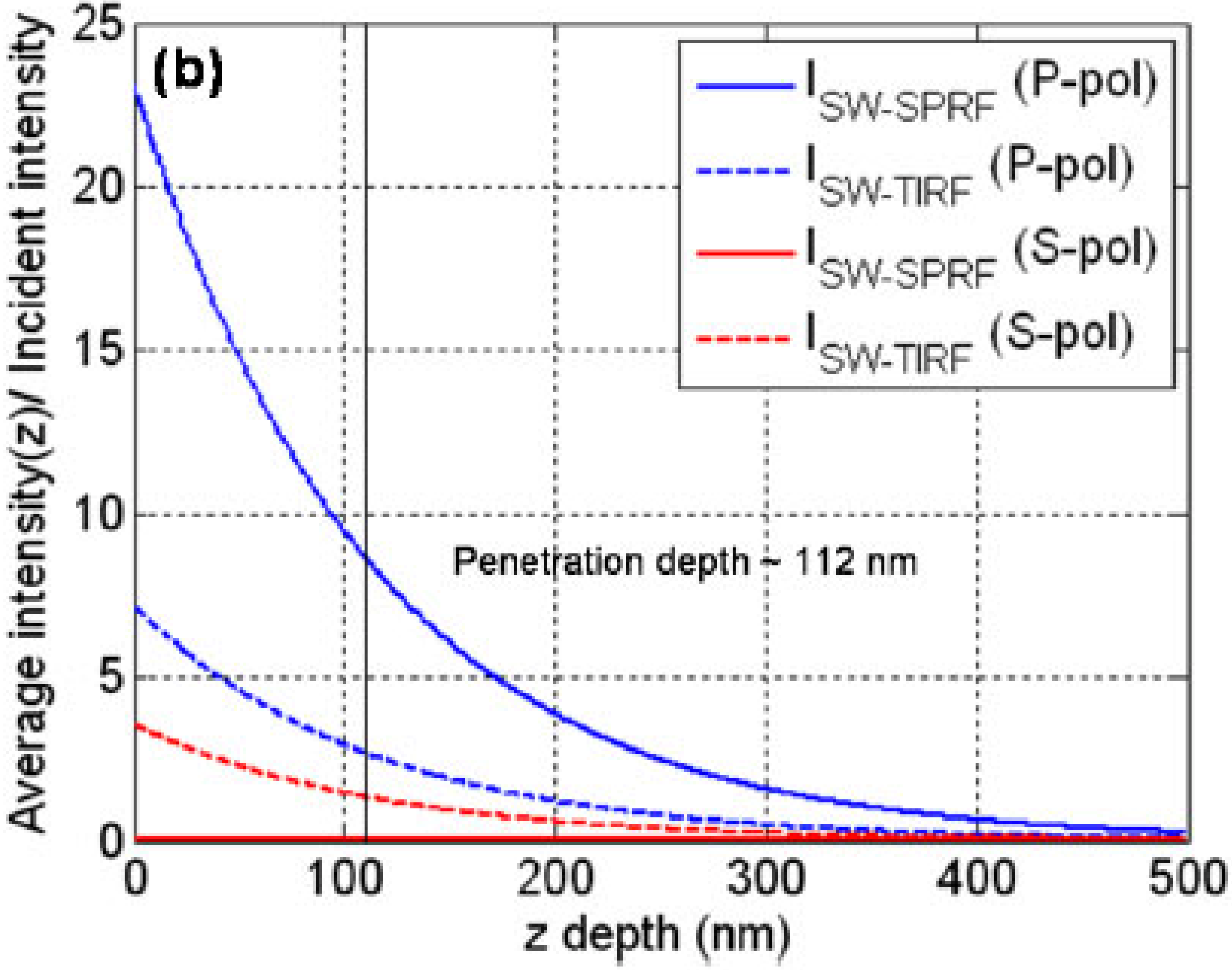


$$x_2 = \left(f_{TB} / M\right) n \sin\theta \qquad p = \frac{\lambda}{2n} \sin\theta$$

$$p(x_1) = \frac{1}{2}\left(\frac{f_{TB}}{M}\right)\left(\frac{f_1}{f_2}\right)\frac{\lambda}{x_1}$$

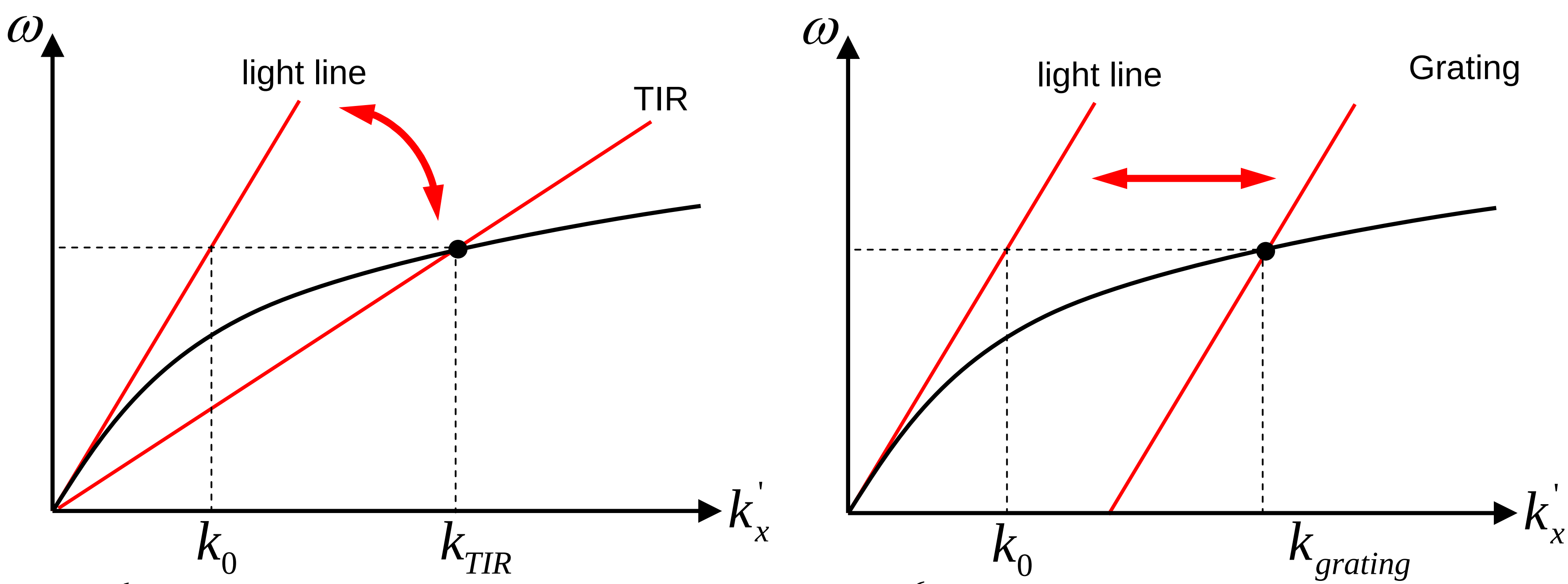
(E. Chung, thesis, MIT, 2007)

SPR field enhancement experiment (IV)



(E. Chung, thesis, MIT, 2007)

Surface plasmon and photon coupling (I)



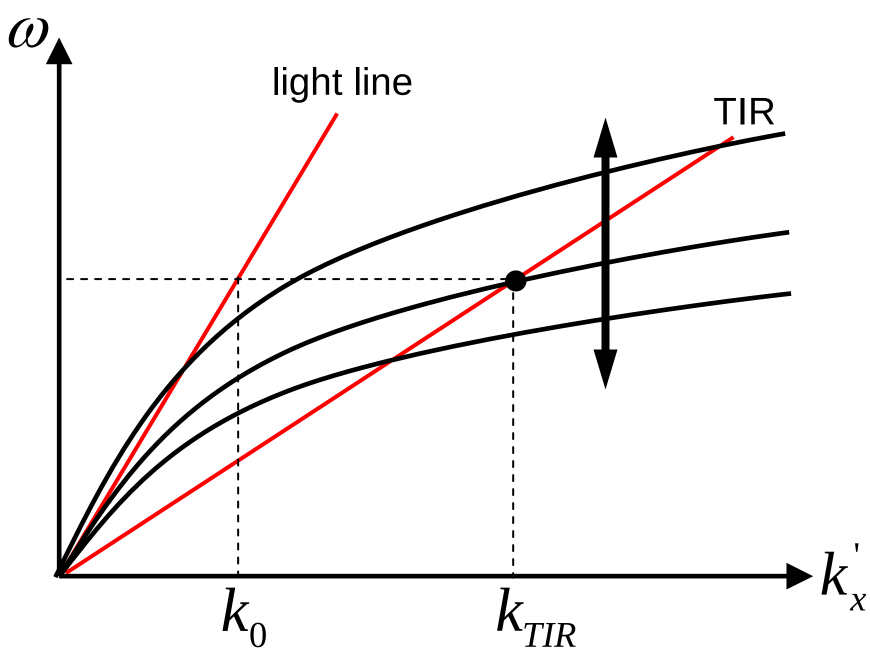
$$\begin{cases} k_{surface\ plasmon} = \dfrac{\omega}{c}\left(\dfrac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}\right)^{1/2} \\ (k_{photon})_x = \sqrt{\varepsilon_0}\,\dfrac{\omega}{c}\sin\theta_0 \end{cases}$$

$$\begin{cases} k_{surface\ plasmon} = \dfrac{\omega}{c}\left(\dfrac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}\right)^{1/2} \\ (k_{photon})_x = \sqrt{\varepsilon_0}\,\dfrac{\omega}{c}\sin\theta_0 + mg \end{cases}$$

k: wavevector, a: grating period, m: diffraction order, ε: dielectric constant

(Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*. 1988, Berlin: Springer)

Surface plasmon and photon coupling (II)

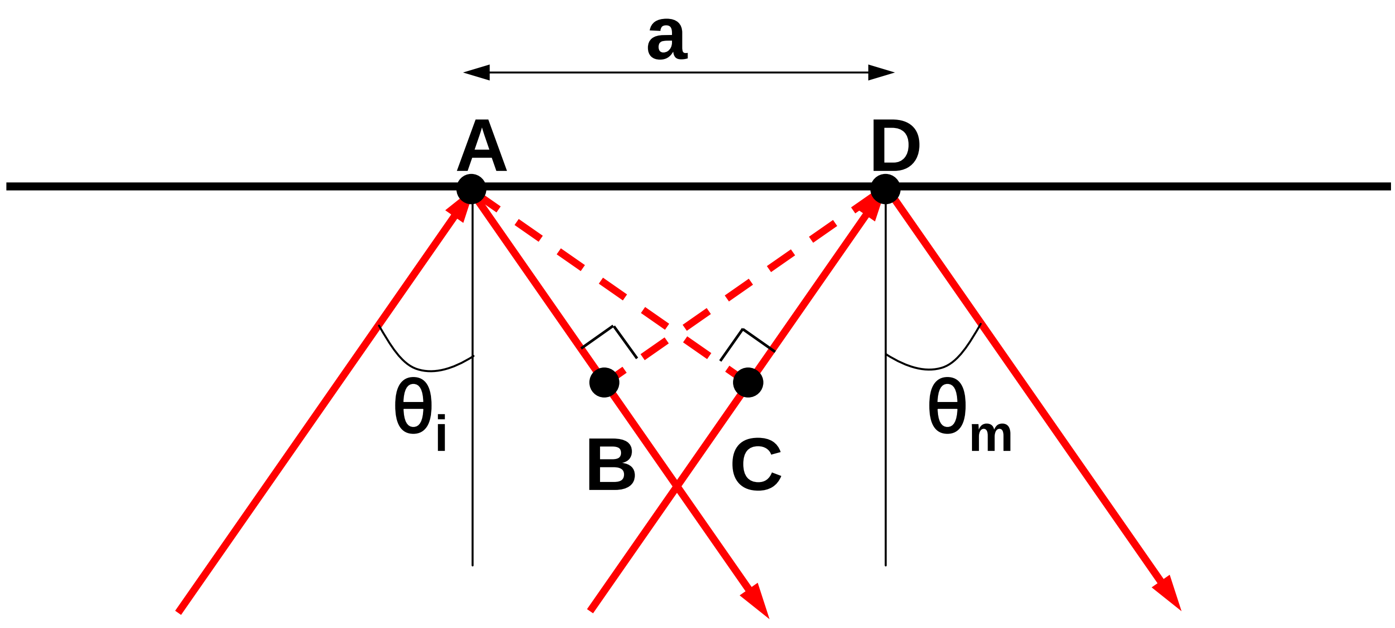


$$
\begin{cases}
k_{surface\ plasmon} = \dfrac{\omega}{c}\left(\dfrac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)^{1/2} \\
(k_{photon})_x = \sqrt{\varepsilon_0}\,\dfrac{\omega}{c}\sin\theta_0
\end{cases}
$$

k: wavevector, a: grating period, m: diffraction order, ε: dielectric constant

(Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*. 1988, Berlin: Springer)

Wave vector change by grating

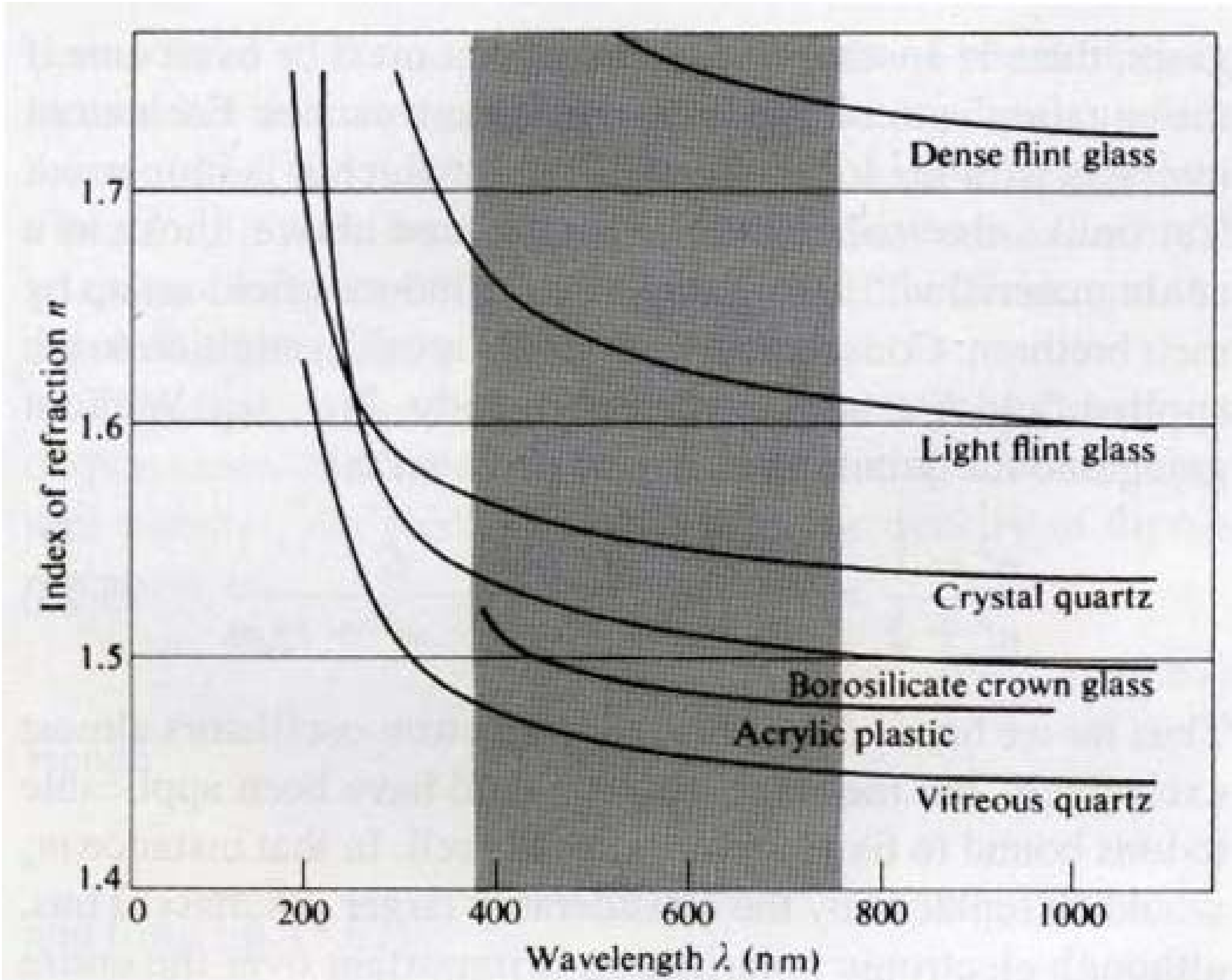


$$AB - CD = a(\sin\theta_m - \sin\theta_i) = m\lambda$$

$$(k_{out})_x - (k_{in})_x = k_0(\sin\theta_m - \sin\theta_i) = \frac{2\pi}{\lambda}\frac{m\lambda}{a} = m\left(\frac{2\pi}{a}\right) = mg$$

(Hecht, *OPTICS*, 2001, Addison Wesley)

Wavelength dependence of various materials



(Hecht, *Optics*. 2002, Addison-Wesley)

Dispersion in atom

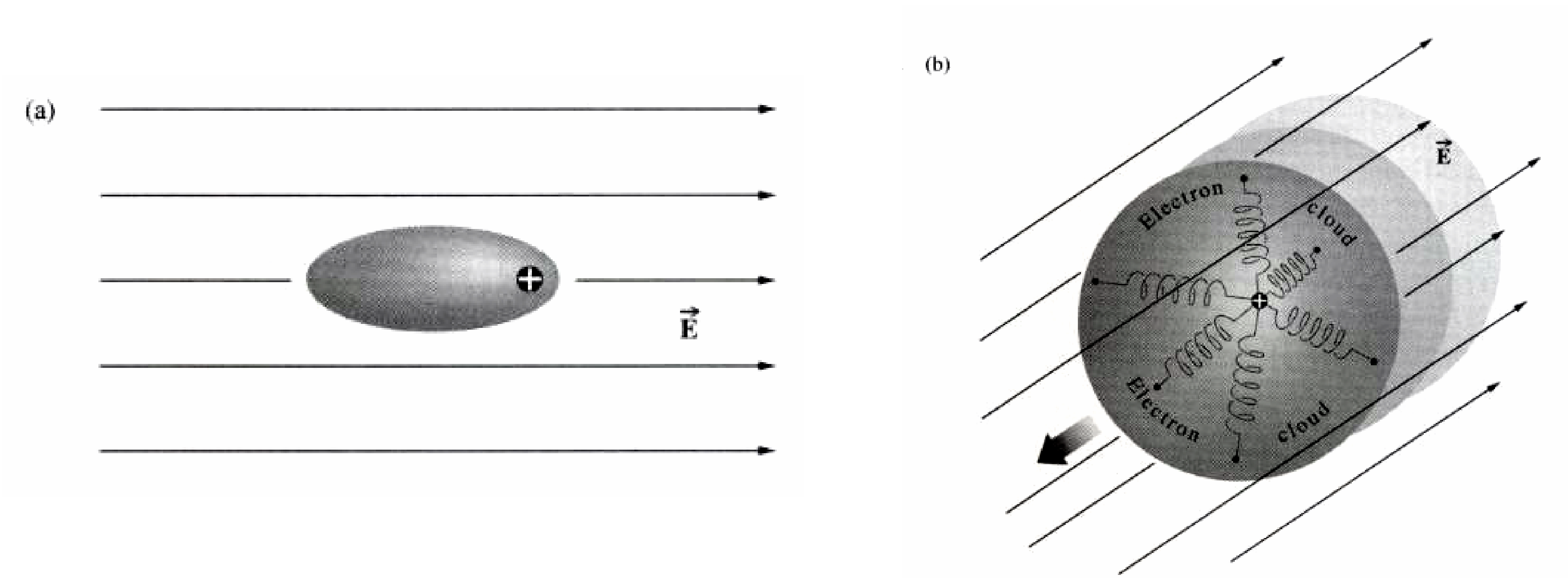


Figure 3.38 (*a*) Distortion of the electron cloud in response to an applied $\vec{E}$-field. (*b*) The mechanical oscillator model for an isotropic medium—all the springs are the same, and the oscillator can vibrate equally in all directions.

(Hecht, *Optics*. 2002, Addison-Wesley)

Dispersion relation of SP (I)

$$z>0 \quad \boldsymbol{H}_2 = (0, H_{y2}, 0)\exp i(k_{x2}x + k_{z2}z - \omega t)$$
$$\boldsymbol{E}_2 = (E_{x2}, 0, E_{z2})\exp i(k_{x2}x + k_{z2}z - \omega t) \qquad (A.1)$$

$$z<0 \quad \boldsymbol{H}_1 = (0, H_{y1}, 0)\exp i(k_{x1}x - k_{z1}z - \omega t)$$
$$\boldsymbol{E}_1 = (E_{x1}, 0, E_{z1})\exp i(k_{x1}x - k_{z1}z - \omega t) \ . \qquad (A.2)$$

These fields have to fulfill Maxwell's equations:

$$\text{rot}\, \boldsymbol{H}_i = \varepsilon_i \frac{1}{c}\frac{\partial}{\partial t}\boldsymbol{E}_i \qquad (A.3)$$

$$\text{rot}\, \boldsymbol{E}_i = -\frac{1}{c}\frac{\partial \boldsymbol{H}_i}{\partial t} \qquad (A.4)$$

$$\text{div}\, \varepsilon_i \boldsymbol{E}_i = 0 \qquad (A.5)$$

$$\text{div}\, \boldsymbol{H}_i = 0 \ , \qquad (A.6)$$

(Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*.1988, Berlin: Springer)

Dispersion relation of SP (II)

together with the continuity relations

$$E_{x1} = E_{x2} \quad \text{(A.7)}$$

$$H_{y1} = H_{y2} \quad \text{(A.8)}$$

$$\varepsilon_1 E_{z1} = \varepsilon_2 E_{z2} \ . \quad \text{(A.9)}$$

From (A.7,8) follows the continuity of

$$k_{x1} = k_{x2} = k_x \ . \quad \text{(A.10)}$$

Equation (A.3) gives

$$\frac{\partial H_{yi}}{\partial z} = -\varepsilon_i E_{xi} \frac{\omega}{c} \quad \text{or}$$

$$+k_{z1} H_{y1} = +\frac{\omega}{c} \varepsilon_1 E_{x1}$$

$$+k_{z2} H_{y2} = -\frac{\omega}{c} \varepsilon_2 E_{x2} \ . \quad \text{(A.11)}$$

(Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*.1988, Berlin: Springer)

Dispersion relation of SP (III)

Equation (A.11) together with (A.7,8) yield

$$\begin{aligned} &H_{y1} - H_{y2} = 0 \\ &\frac{k_{z1}}{\varepsilon_1} H_{y1} + \frac{k_{z2}}{\varepsilon_2} H_{y2} = 0 \ . \end{aligned} \tag{A.12}$$

To obtain a solution, the determinant D_0 has to be zero

$$D_0 = \frac{k_{z1}}{\varepsilon_1} + \frac{k_{z2}}{\varepsilon_2} = 0 \ . \tag{A.13}$$

This is the dispersion relation of the SPs in the system Fig. A.1. Further we get from (A.3,4,11)

$$k_x^2 + k_{zi}^2 = \varepsilon_i \left(\frac{\omega}{c}\right)^2 \ . \tag{A.14}$$

From (A.13) together with (A.14) follows

$$k_x = \frac{\omega}{c} \left(\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}\right)^{1/2} \ . \tag{A.15}$$

(Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*.1988, Berlin: Springer)

Dielectric function of gold

Table A.2. Dielectric function of gold (see also caption to Table A.1)

λ [Å]	Real part	Imaginary part
8200	−23.8	2.19
8100	−23.1	2.08
8000	−22.3	1.99
7900	−21.5	1.90
7800	−20.7	1.82
7700	−20.0	1.74
7600	−19.3	1.67
7500	−18.6	1.62
7400	−18.0	1.56
7300	−17.4	1.52
7200	−16.7	1.48
7100	−16.1	1.45
7000	−15.4	1.43
6900	−14.7	1.42
6800	−14.1	1.41
6700	−13.4	1.40
6600	−12.7	1.41
6500	−12.1	1.42
6400	−11.4	1.45
6300	−10.8	1.47
6200	−10.1	1.50
6100	−9.5	1.54
6000	−8.9	1.59
5900	−8.2	1.65
5800	−7.5	1.72
5700	−6.8	1.80
5600	−6.1	1.88
5500	−5.5	1.98
5499	−4.7	2.20
5300	−3.8	2.44
5200	−3.2	2.80
5100	−2.5	3.26
5000	−2.0	4.12

(Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*.1988, Berlin: Springer)

Source of Noise in Optical Detectors

(1) Optical shot noise (N_s) –
inherent noise in counting a finite number of photons per unit time

(2) Dark current noise (N_d) –
thermally induced "firing" of the detector

(3) Johnson noise (N_J) –
thermally induced current fluctuation in the load resistor

Since the noises are uncorrelated, the different sources of noise add in quadrature

$$N^2 \propto N_S^2 + N_d^2 + N_J^2$$

(MIT 2.710 Optics lecture note)