Content of this lecture

1. Excitation of SPPs
   - Prism coupling
   - Excitation by highly focused beam
   - Grating coupling
   - Excitation by scattering
   - Near-field excitation
   - Other coupling schemes
2. Characterization of SPPs
   - Near-field microscopy
   - Leakage radiation microscopy
   - Fluorescence imaging
   - Scattered light imaging

characterization: 检测

1. Excitation of SPPs

- To excite SPPs, the wave vector of incident light should satisfy:

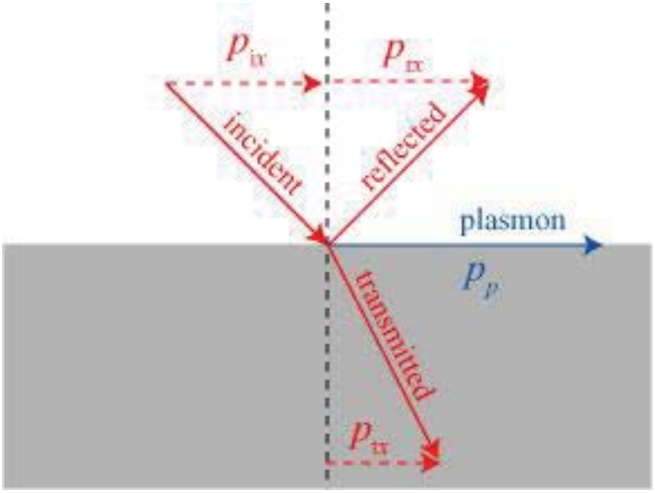
$$k_x^{\mathrm{inc}} = \beta_{\mathrm{SPP}}$$ (also called "phase-matching condition")

Why? – conservation of the transverse momentum of photons!

Momentum of photons:

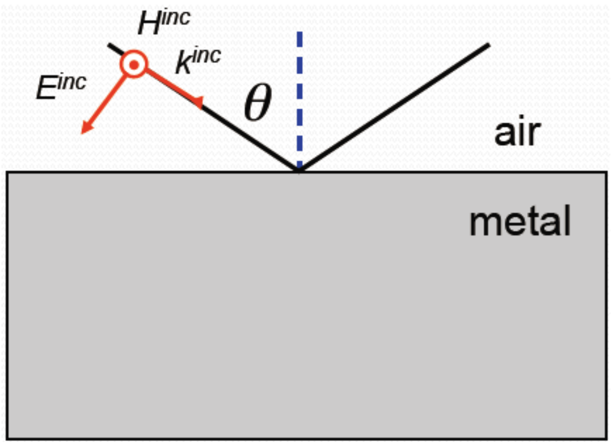
$$\mathbf{P} = \hbar \mathbf{k}$$

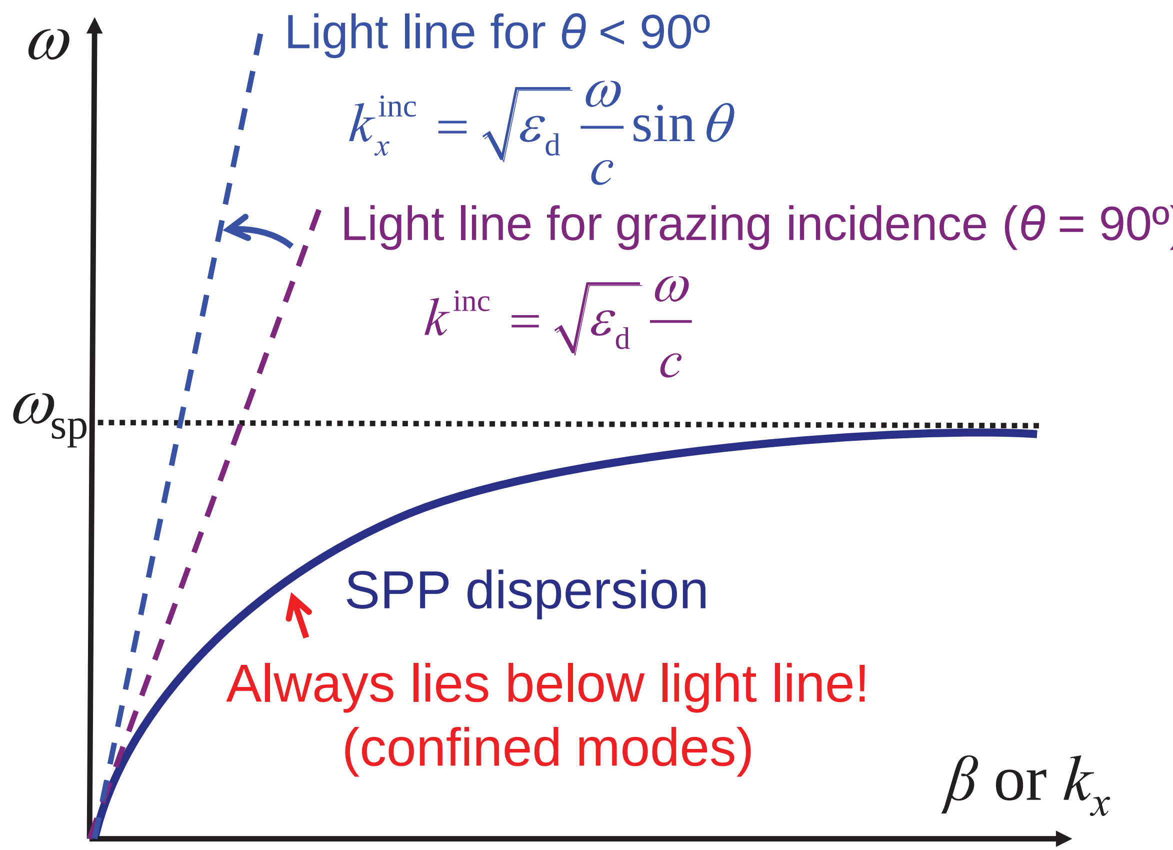
($\hbar$: reduced Planck constant)



conservation: 守恒， momentum: 动量

- Can SPPs be excited just by shining light on a flat metal surface?





x-component of the incident wavevector:

$$k_x^{\text{inc}} = k^{\text{inc}}\sin\theta = \sqrt{\varepsilon_{\text{d}}}\,\frac{\omega}{c}\sin\theta$$

- No intersection → phase matching condition cannot be satisfied → no in-coupling of light & no out-coupling of SPPs (∴confined field)
- Therefore, k_x^{inc} must be increased by **some "tricks"** to match β_{SPP}

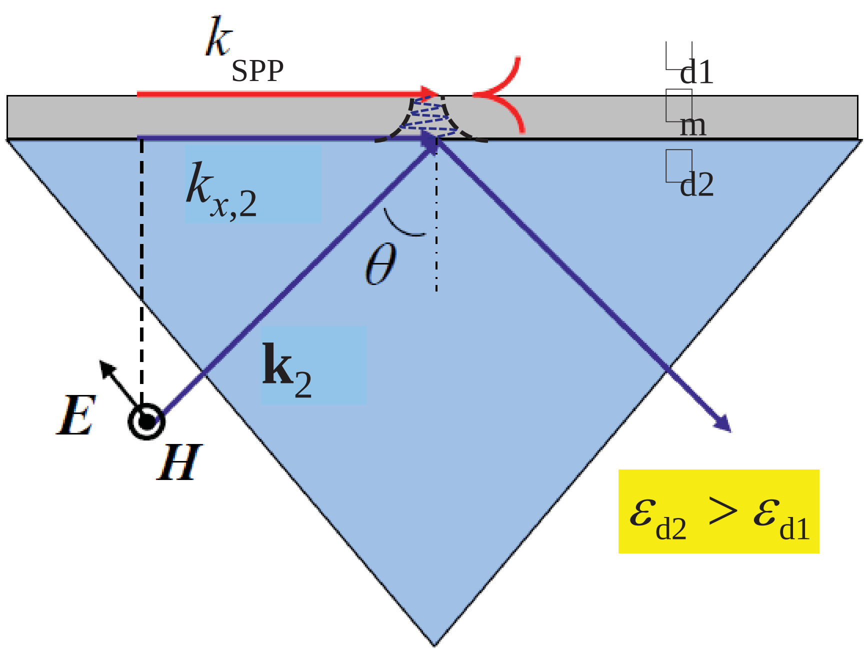
intersection: 交叉

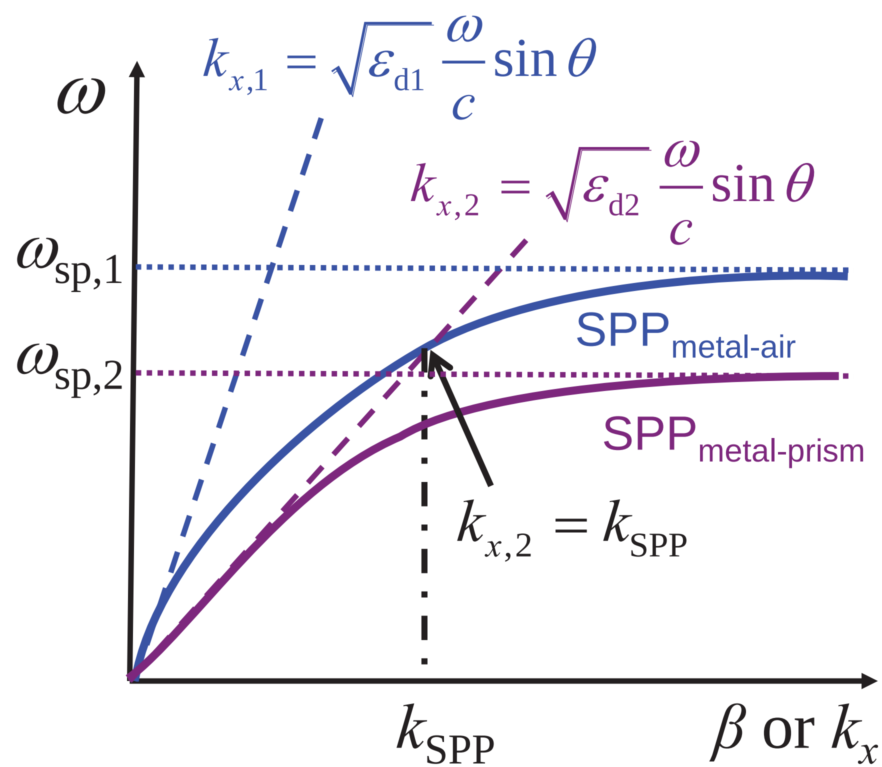
(1) Prism coupling

- In the prism, create evanescent wave by total internal reflection (TIR)
- Evanescent wave tunnels through the thin film to the air-metal surface
- Strong coupling when $k_{SPP} = k_{x,2}$

momentum matching

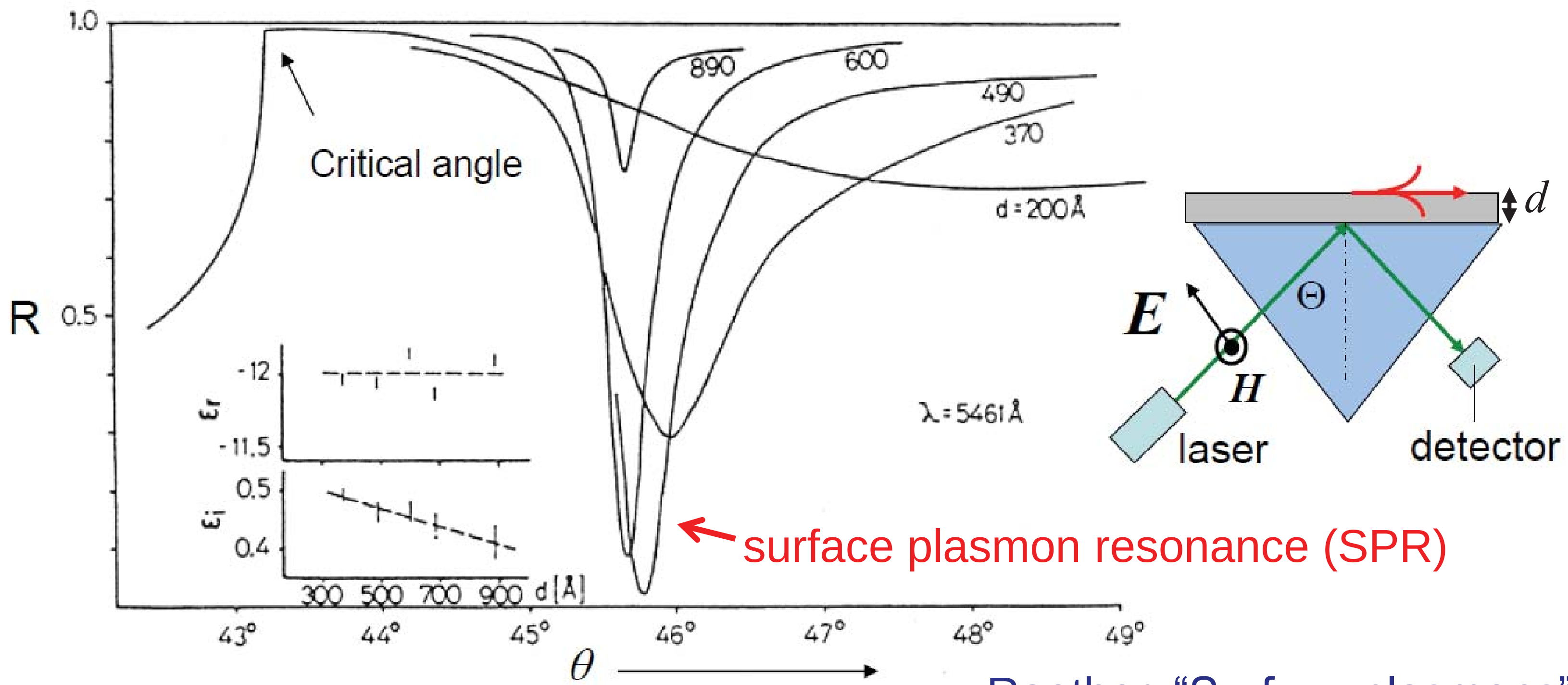
energy matching





total internal reflection: 全內反射，tunnel: 隧穿

- At SPP excitation, energy is transferred from incident light to SPPs → a minimum in the reflected intensity is observed

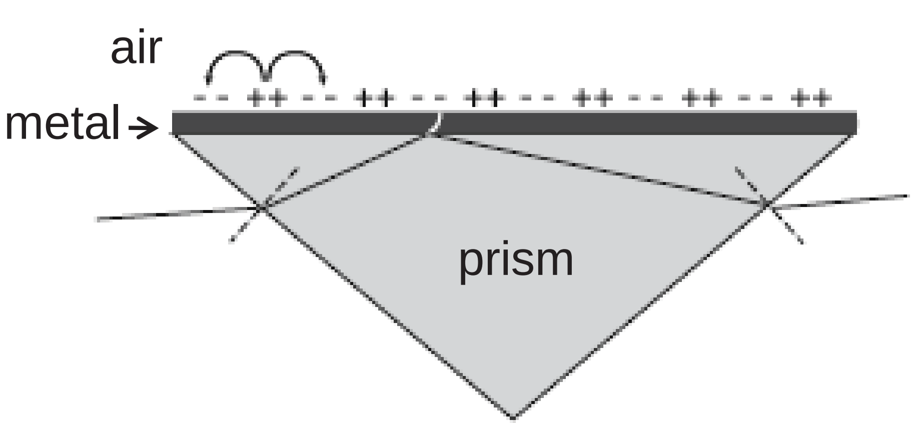


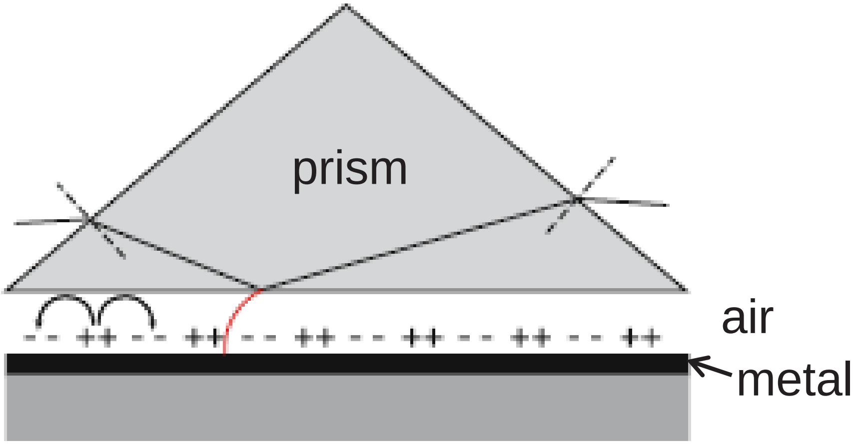
Raether, “Surface plasmons”

- Dependence on film thickness: there is an optimum thickness for perfect coupling
- Resonance width related to the damping (loss) of SPPs
- Excited SPPs are leaky waves: leakage of radiation into the prism
- Minimum caused by destructive interference of leakage & direct TIR

surface plasmon resonance: 表面等离激元共振，leakage: 泄漏，destructive: 相消的

Two coupling configurations:





Kretschmann configuration

- Evaporation of metal film on the prism is needed

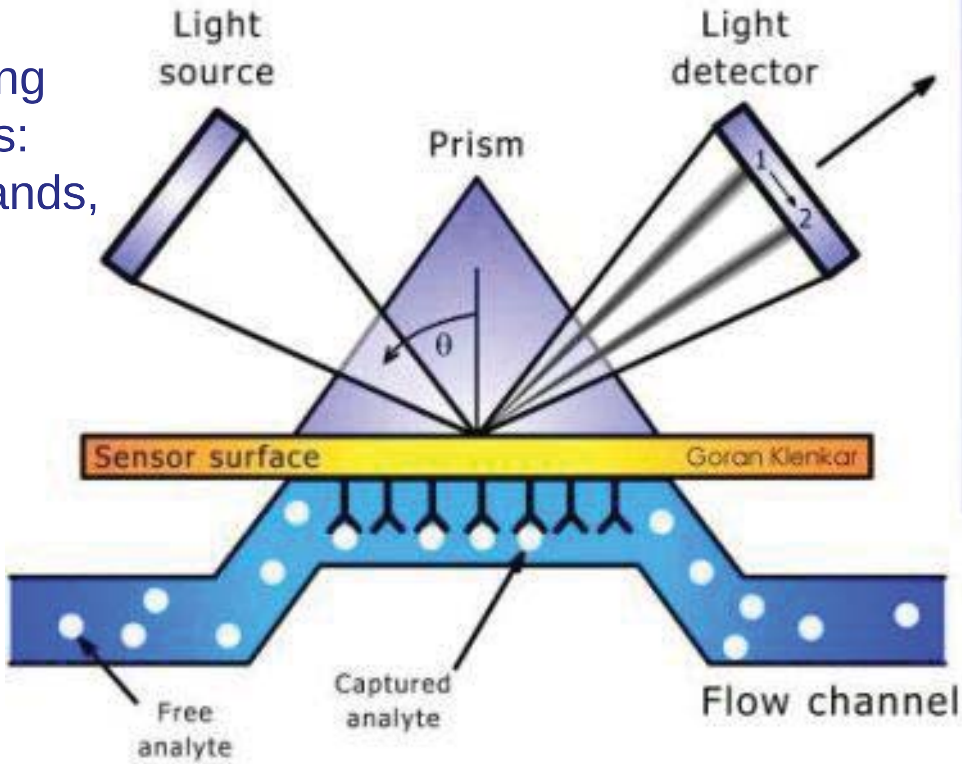
Otto configuration

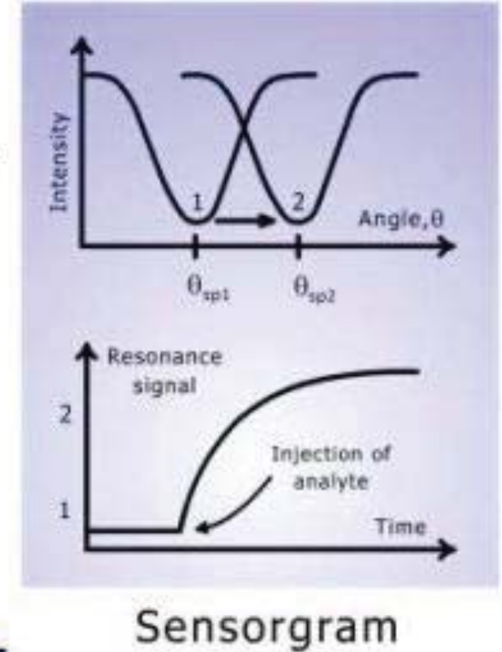
- Avoid direct contact with the metal surface (e.g., for studies of the surface quality)
- The air gap should be well controlled to be small enough

configuration: 设置， evaporation: 蒸镀

Application example: biosensing

For monitoring biomolecules: proteins, ligands, DNA, etc.





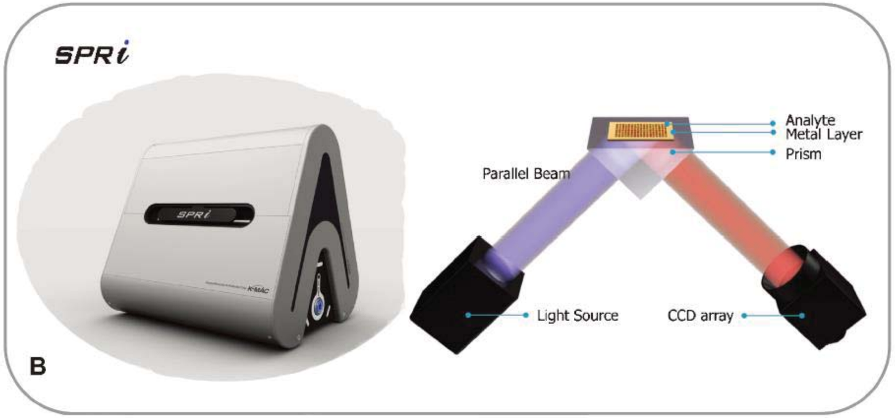
Advantages:
– real-time sensing
– no labeling

Principle:

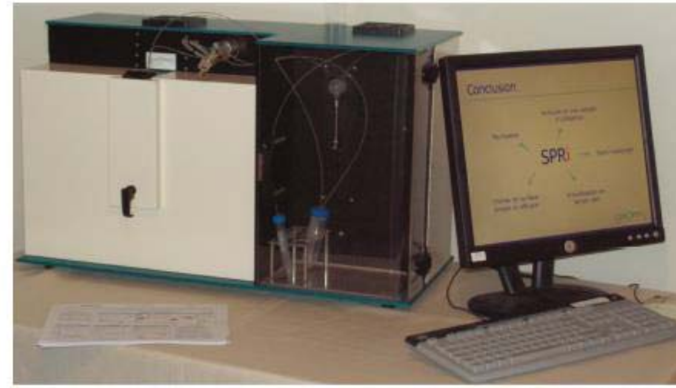
- SPR is surface sensitive
- Antibodies are attached to gold surface
- Complementary antigen (analyte) binds to the antibodies → refractive index □$_d$ change → SPR-dip shift (monitored signal)

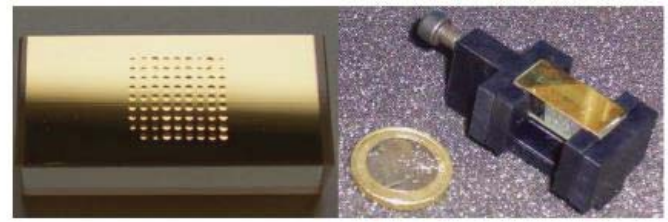
biosensor: 生物传感器，antibody: 抗体，antigen: 抗原，analyte: 被分析物，ligand: 配位体，labeling: 标记

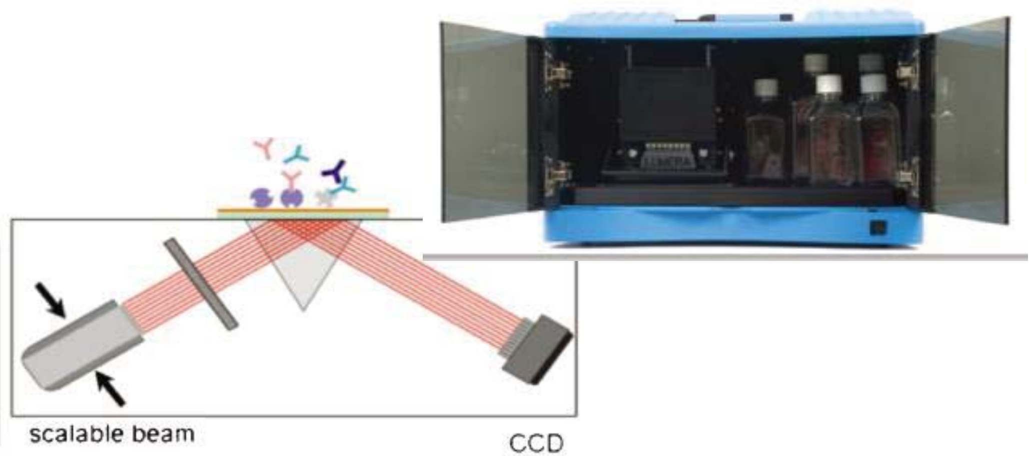
Commercial SPR instruments:



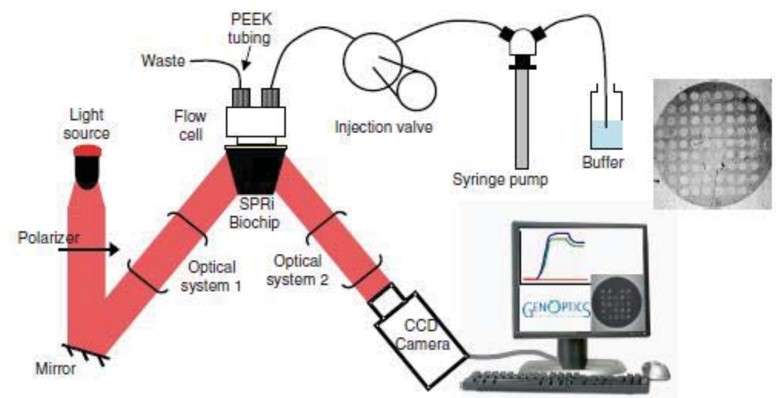
SPRi system of K-MAC (Daejeon, Korea)





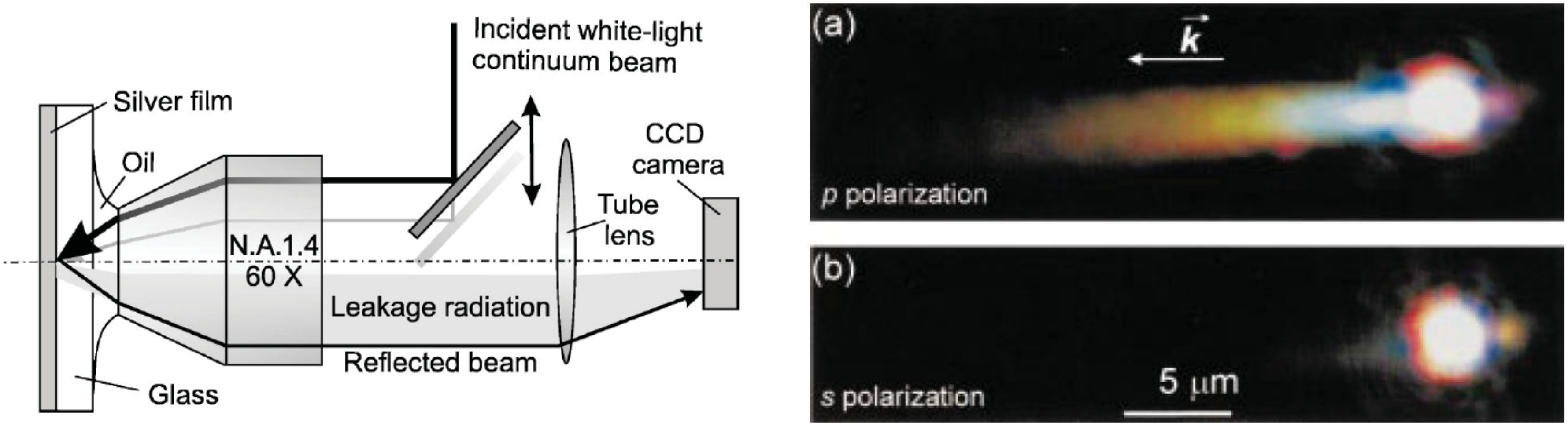


The Proteomic Processor of Lumera (Bothell, WA, USA)



SPRi-Plex and SPRi-Lab+ system of GenOptics (Orsay, France)

(2) Excitation by highly focused optical beams



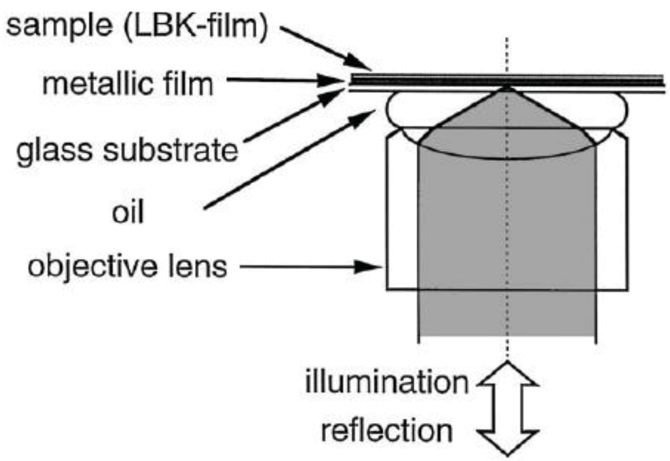
Bouhelier and Wiederrecht, OL **30**, 884 (2005)

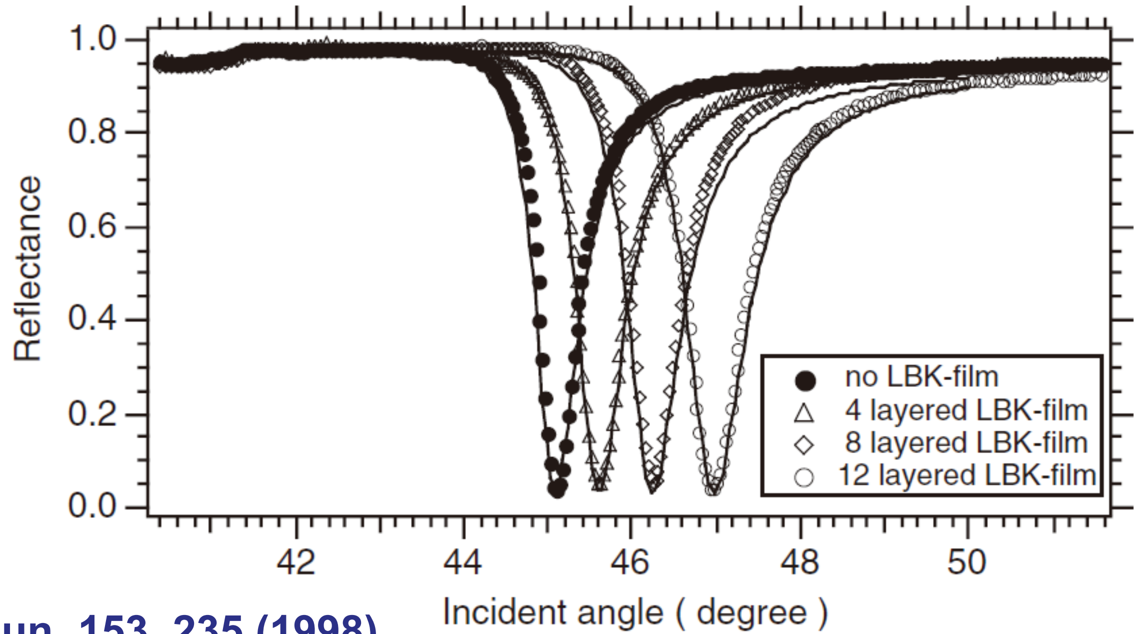
- Is a variation of the prism coupling – an oil-immersion objective of high numeric aperture is used instead of the prism
- Off-axis entrance of the beam → excitation at an expected angle > θc
- Highly focused beam → allows for localized SPP excitation
- Leakage radiation → observation of the SPP excitation

oil-immersion objective: 油浸物镜，numeric aperture: 数值孔径，off-axis: 离轴

Application example: measurement of ultra-thin film thickness

- Measurement of Langmuir-Blodget-Kuhn (LBK) film thickness





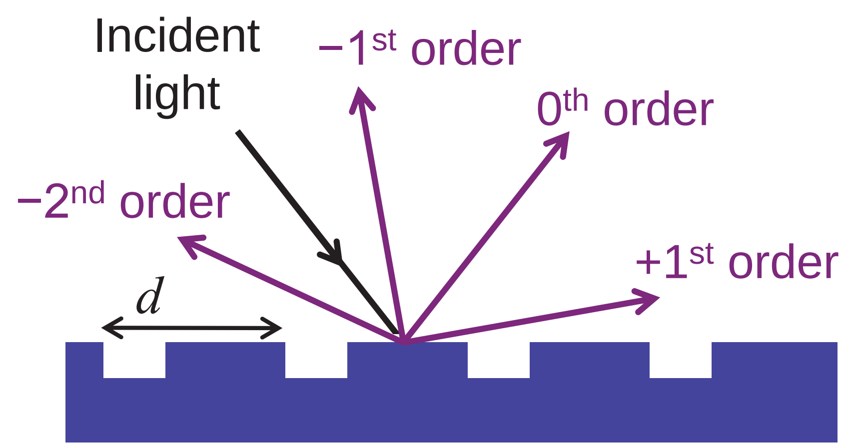
H. Kano and W. Knoll, Opt. Commun. 153, 235 (1998)

- Principle: Variation of film thickness → change effective ε_d → shift of SPR
- Coupling angle strongly depends on the film thickness of the LBK film
- Measured results: LBK thicknesses of 3.5nm, 7.3nm, 11.15nm
- Detection of just a few LBK layers is feasible!

LBK film: 功能分子转移膜

(3) Grating coupling

- Grating can generate multiple diffraction orders (propagating & evanescent).

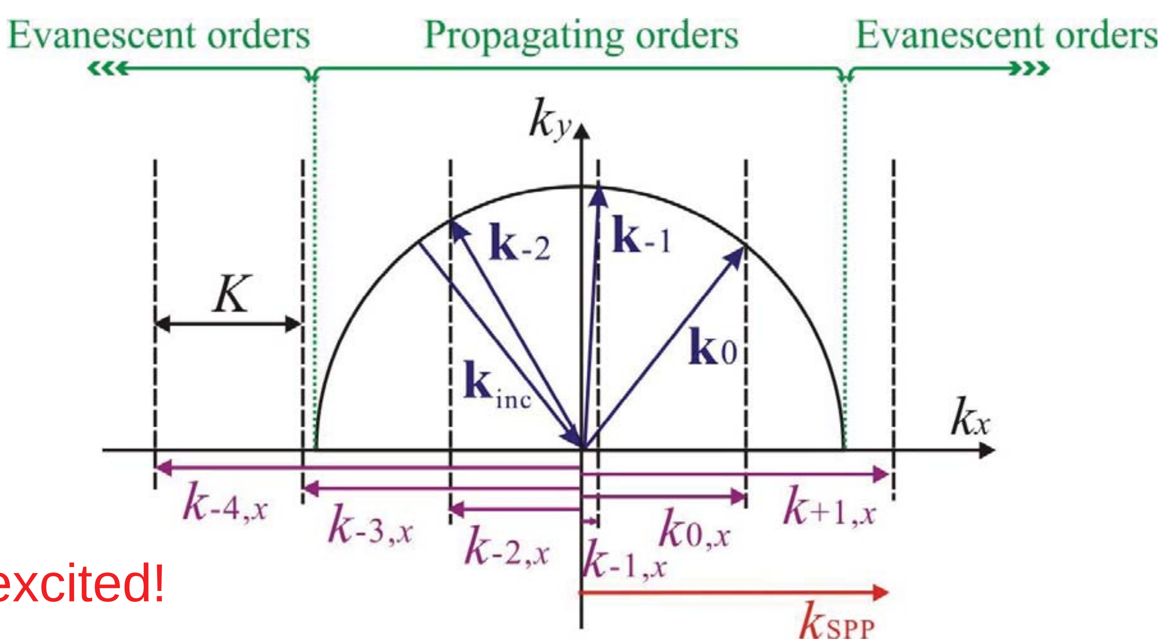


- m^{th}-order wavevector satisfies:

$$k_{m,x} = k_{\text{inc},x} + mK$$

(= grating equation, check it by yourself)

$$K = \frac{2\pi}{d}$$



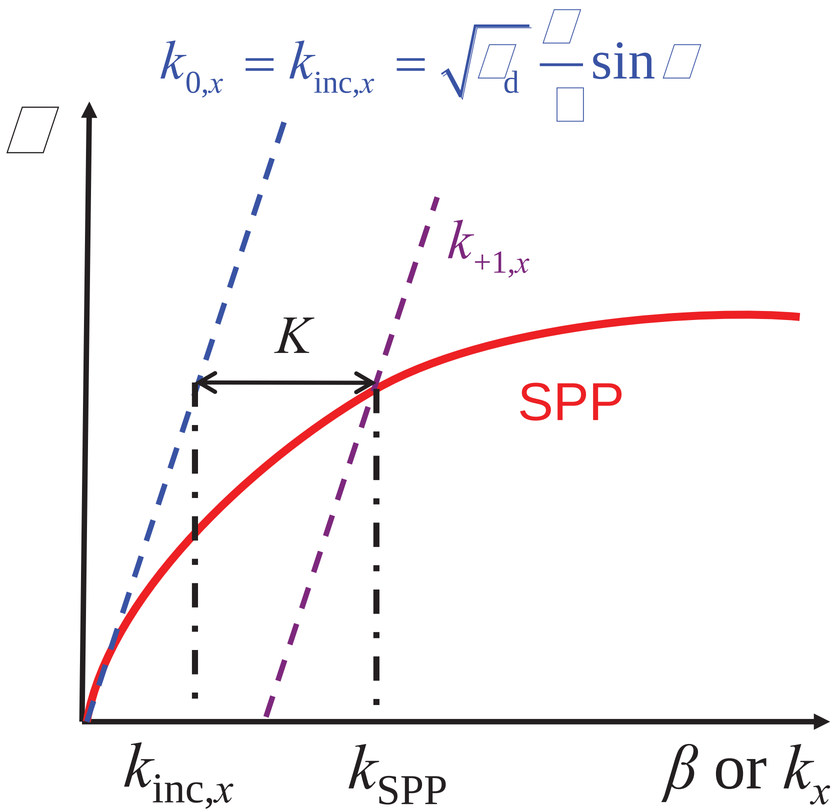
- Since $k_{\text{SPP}} > k_{\text{inc}}$, only the evanescent orders may phase-match with SPPs:

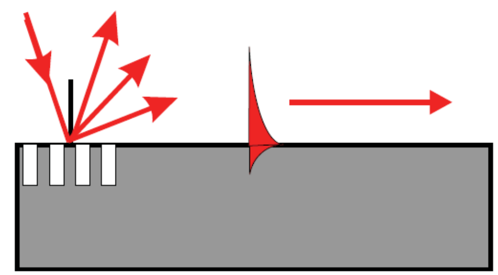
$$k_{\text{SPP}} = k_{m,x} = k_{\text{inc},x} + mK$$

In this way, the SPPs are excited!

grating: 光栅， evanescent: 倏逝的

Understand the grating coupling in the dispersion diagram:



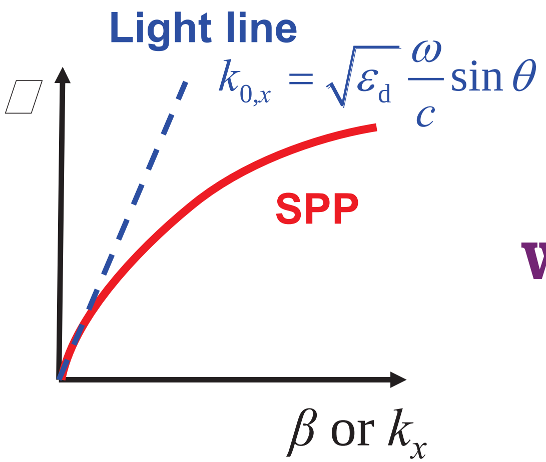


$$k_{\mathrm{SPP}} = k_{m,x} = k_{\mathrm{inc},x} + mK$$

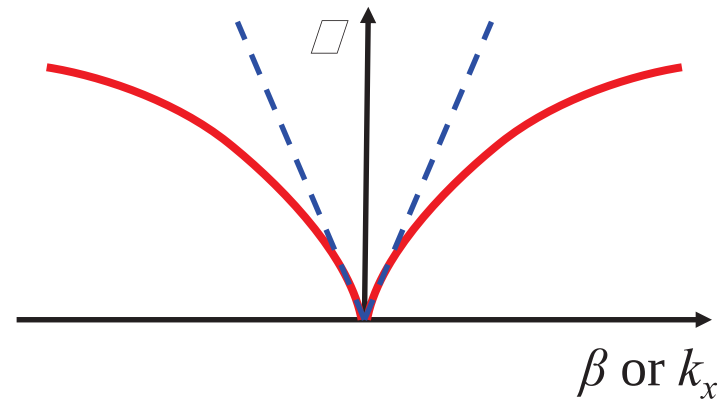
It seems that only positive orders can excite SPPs?

– No! Both positive & negative orders can excite!

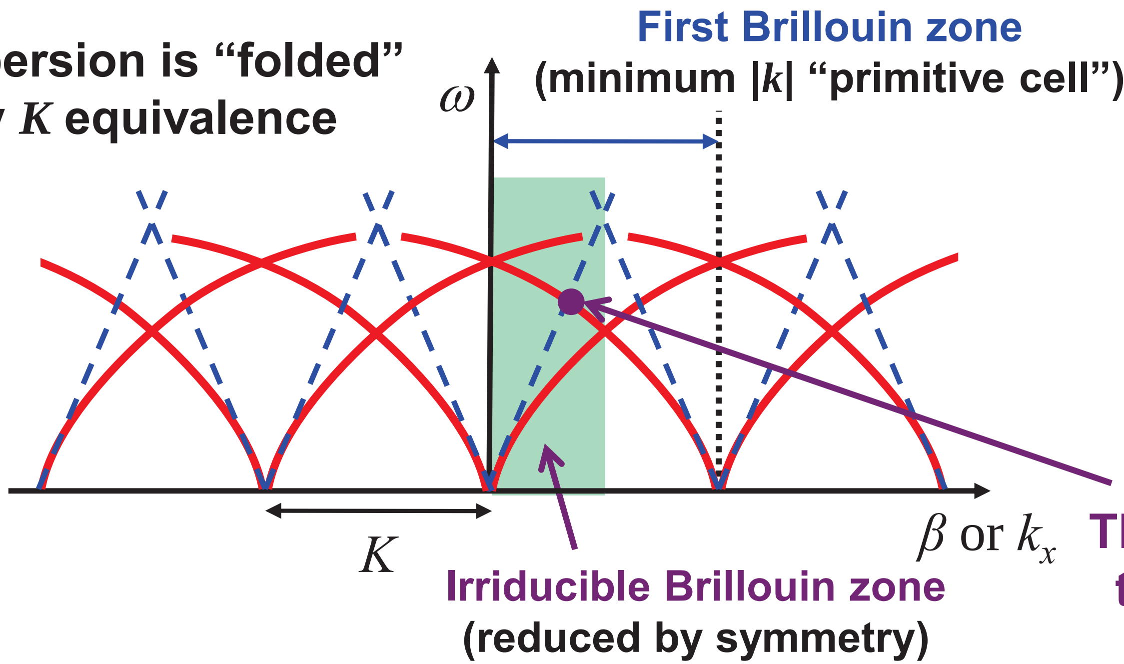
More about the dispersion diagram:



What happens at $-k$?



Dispersion is "folded" by K equivalence



Periodic condition

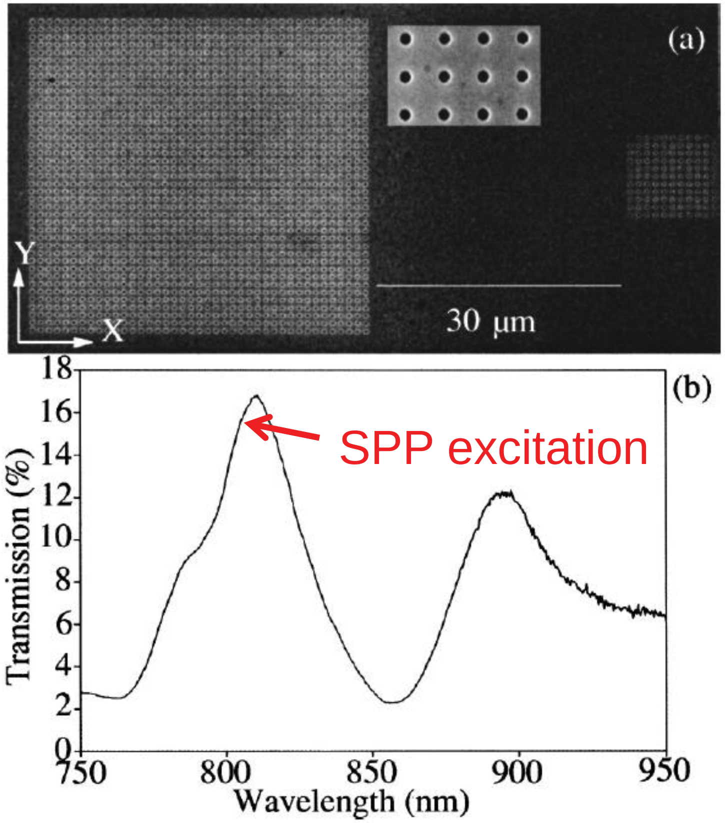
$$k_{m,x} = k_{\mathrm{inc},x} + mK$$

The cross points between the red and blue curves indicate the coupling!

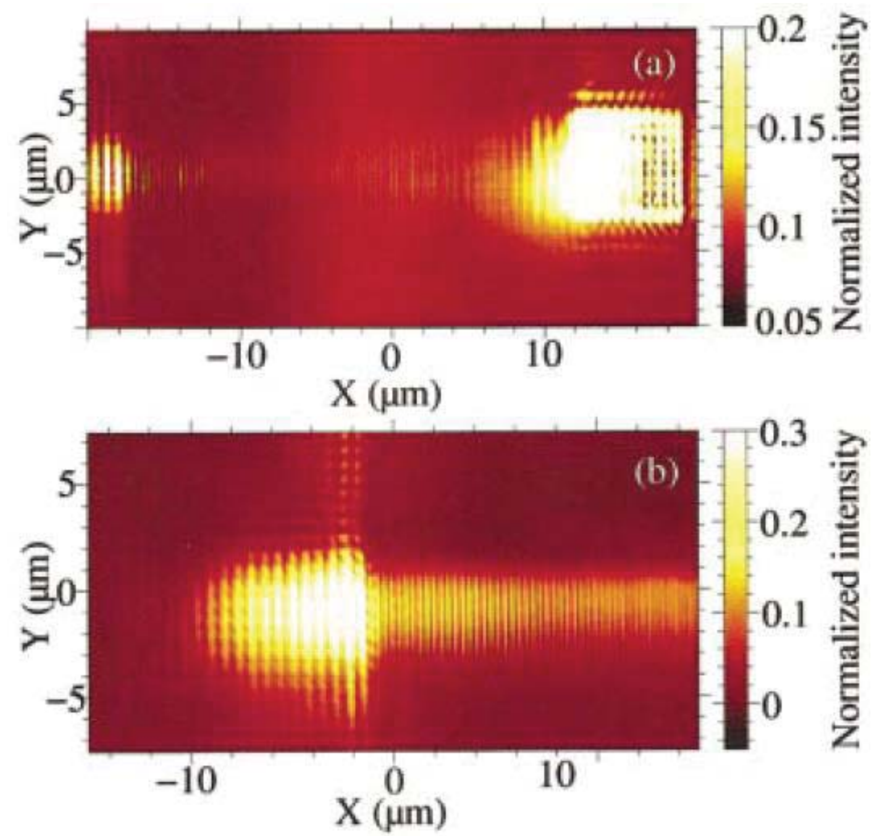
fold: 折叠，Brillouin zone: 布里渊区，irriducible: 不可约的

The reverse process can also take place: SPPs propagating along a grating surface can couple to light and thus radiate.

Experiment: SPPs excited by the right small grating and decoupled by the left big grating (□= 760 nm)



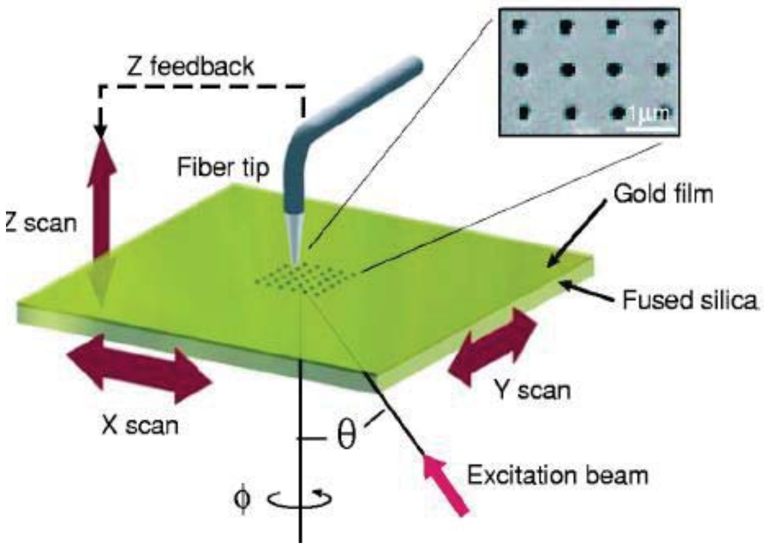
Devaux et al., APL □□, 4936 (2003)

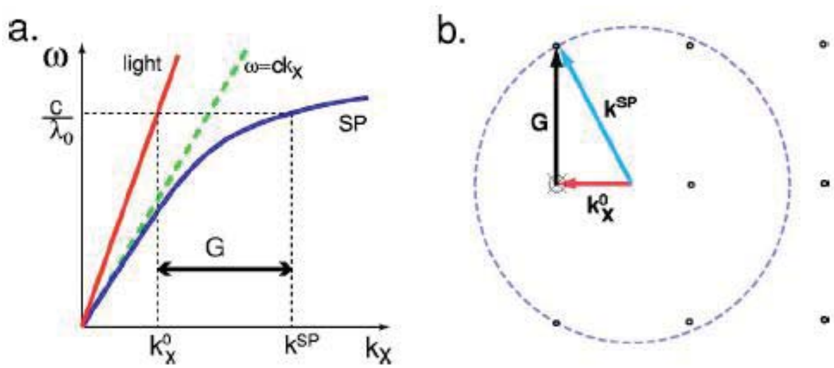


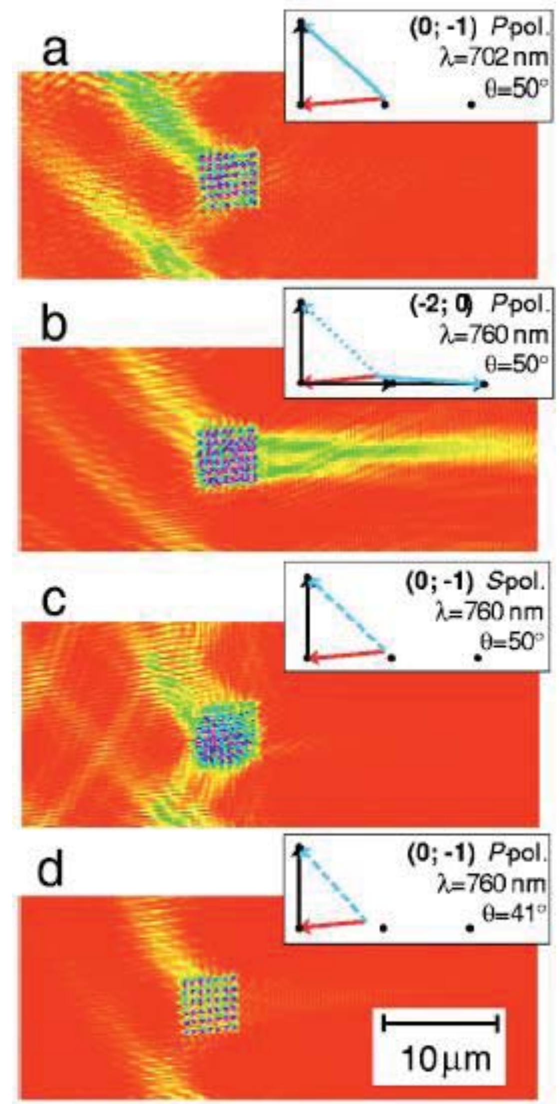
Near-field optical image (λ = 800 nm)

reverse: 相反的，decouple: 解耦合

Excitation and beaming of SPPs by different orders of a 2D grating:



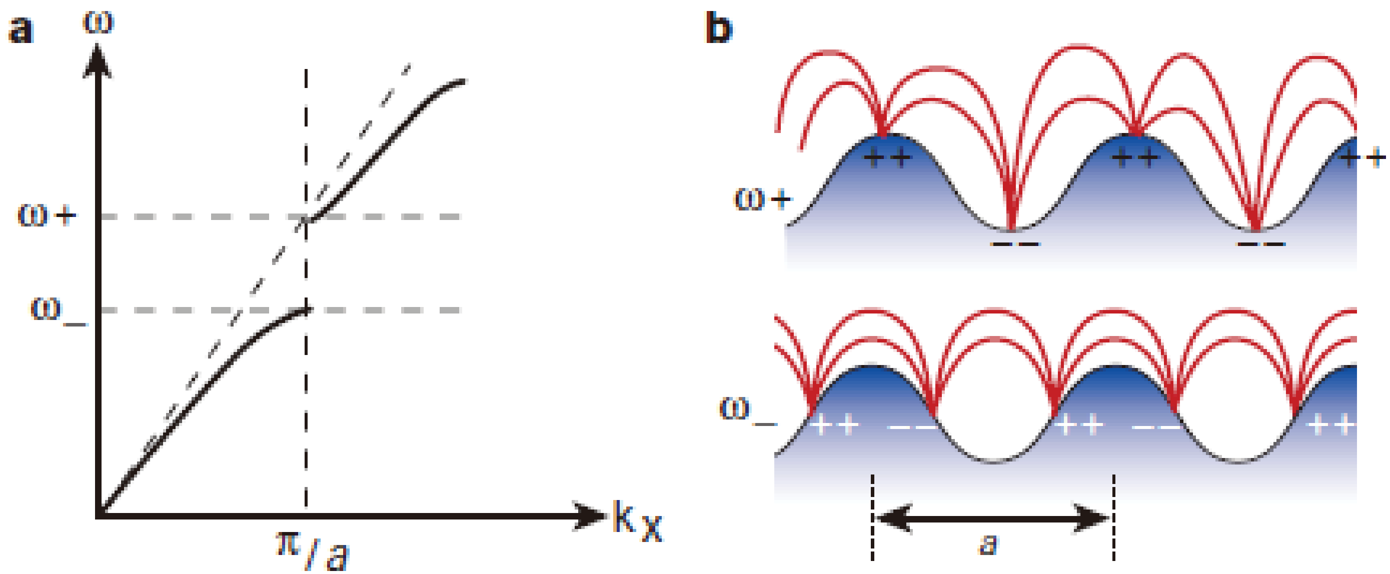




Egorov et al., PRB **70**, 033404 (2004).

SPP photonic bandgap structures:

- When grating is deep □ □no longer small perturbation of the surface
- Significant changes to the SPP dispersion
- When $d \sim \lambda_{SPP}/2$: scattering leads to formation of SPP standing waves → opening of an SPP stop band at the Brillouin zone edge



Barnes et al., Nature **424**, 824 (2003).

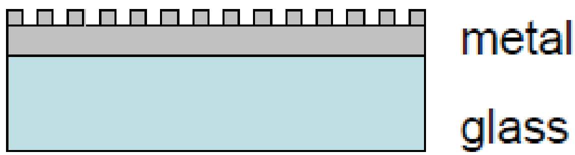
In analogy to photonic crystals, named “surface polaritonic crystals”

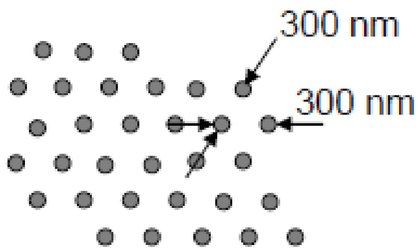
Zayats and Smolyaninov, J. Opt. A: Pure Appl. Opt. **5**, S16 (2003).

bandgap: 带隙， perturbation: 扰动， formation: 形成， standing wave: 驻波， stop band: 禁带

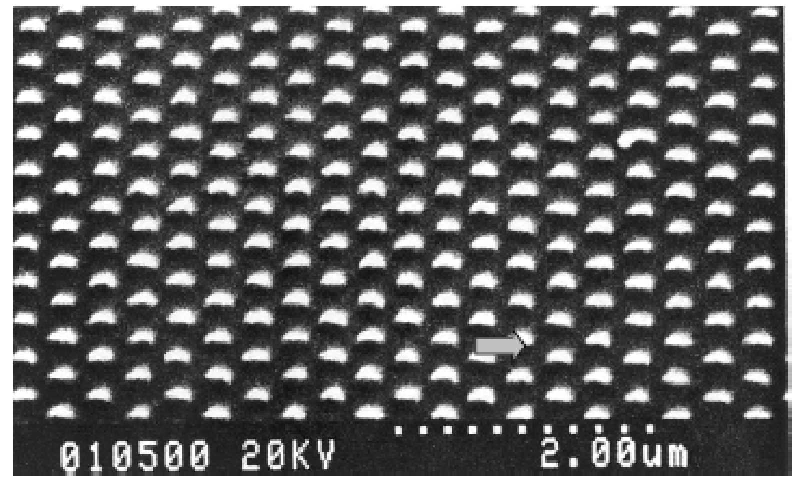
Full photonic bandgap for SPPs

- Hexagonal array of metallic dots





Scanning Electron Microscopy image (tilted)

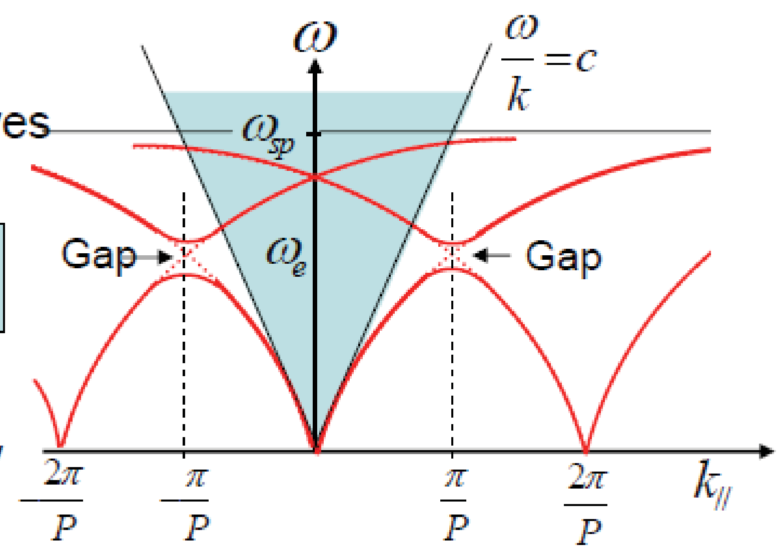


S.C. Kitson, Phys Rev Lett. **77**, *2670 (1996)*

- Array causes coupling between waves for which:

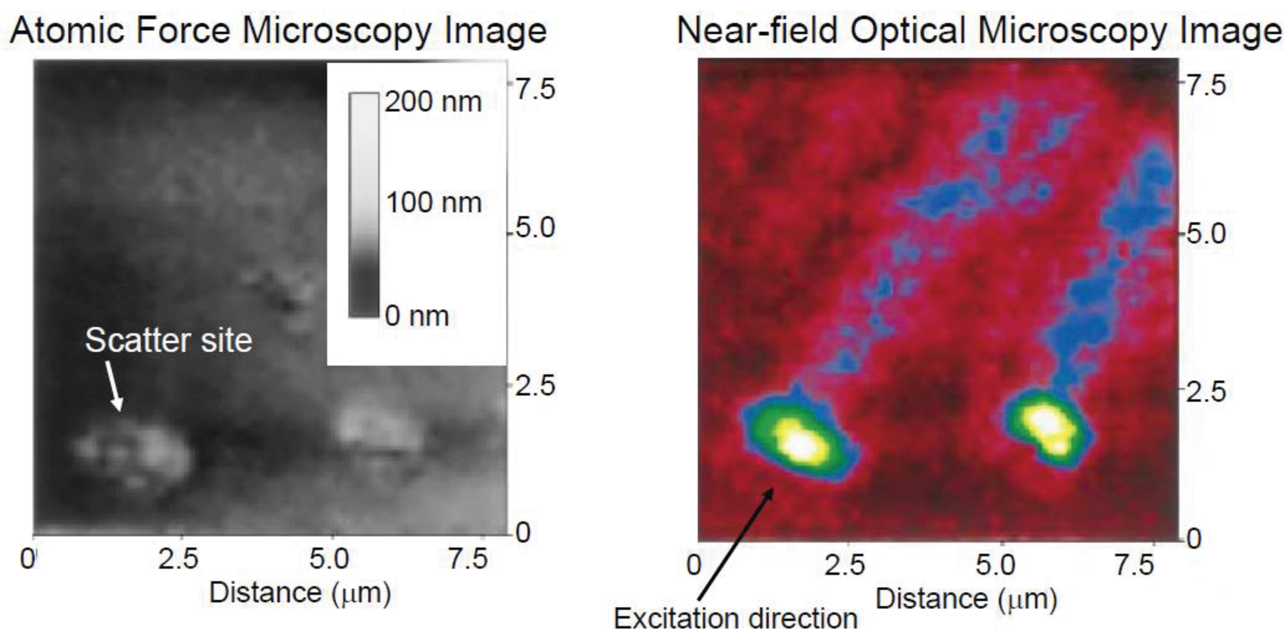
$$k_{sp} = \pi/P \text{ or } \lambda_{sp} = 2\pi/k_{sp} = 2P$$

- Gap opens up at the zone boundary

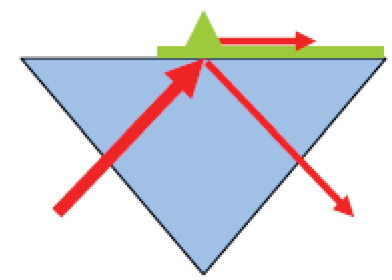


hexagonal: 六角形的

(4) Excitation by scattering



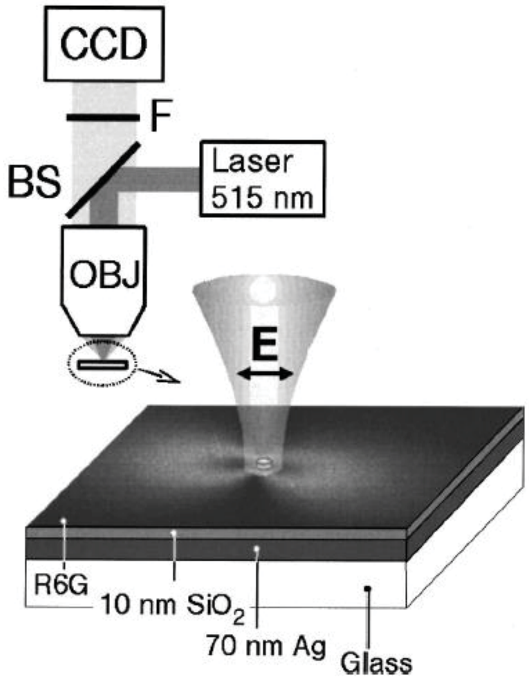
Smolyaninov, PRL **77**, 3877 (1996)



- Random structures such as single holes, sharp edges, particles, and defects can locally excite SPPs.
- It happens when the defect dimension $a << \lambda_0$, why?
- Scattering generates a broad spectrum of K vectors (stemming from the spatial Fourier transform of the defect) in which a solution to the coupling condition $k_{SPP} = k_{inc,x} + K$ can be found. (Homework)
- It also implies that surface defect is a loss channel for SPP propagation!

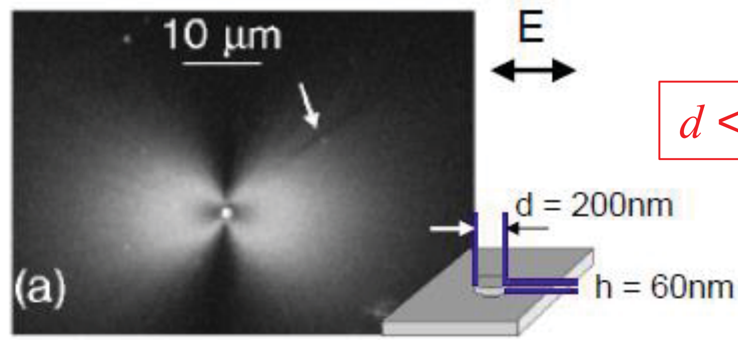
scattering: 散射，random: 随机的，spatial: 空间的，Fourier transform: 傅立叶变换，defect: 缺陷

Ditlbacher et al., APL **80**, 404 (2002).

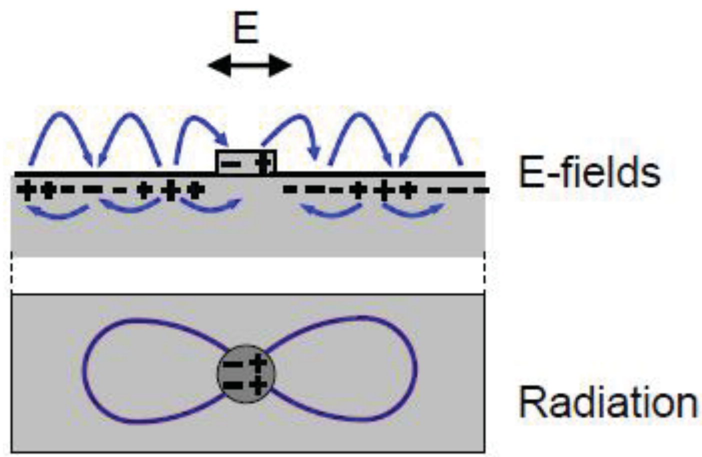


Phase-matching: $k_{\mathrm{SPP}} = k_{\mathrm{inc},x} + K$

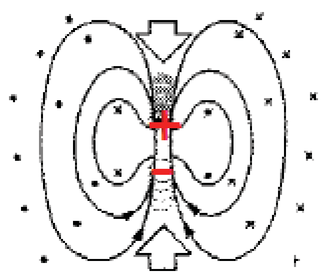
Dipolar radiation pattern



$d << \lambda_0$



Radiation of dipole ⊥ oscillation direction

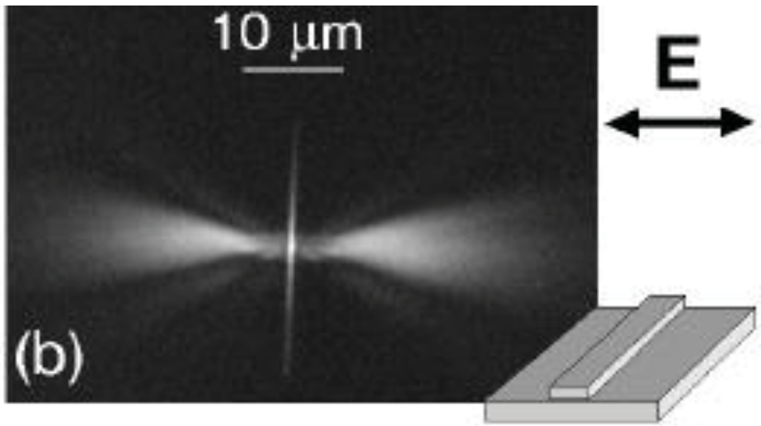


- Dipole radiation in the direction of charge oscillation?! Why?

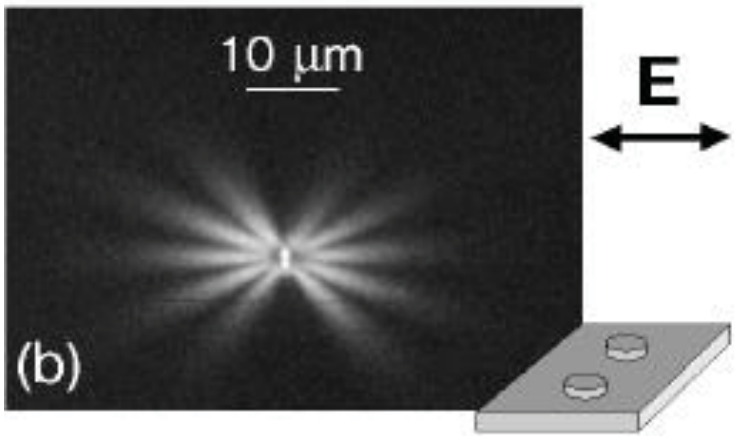
Plasmon wave is mainly longitudinal!

Ditlbacher et al., APL **80**, 404 (2002).

Scattering by sharp edge



Scattering by two dots



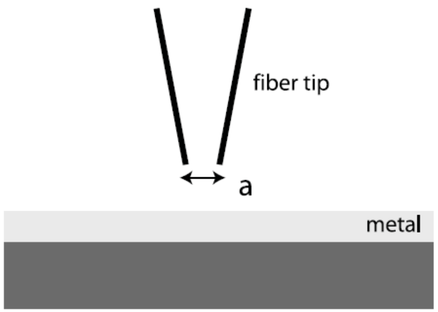
- Radiation pattern is more directional
- If illumination over whole line → radiation ⊥ line

- Pattern results from the interference of SPPs excited by the two dipoles

illumination: 照明， interference: 干涉， pattern: 图案

(5) Near-field excitation

Hecht et al., PRL **77**, 1889 (1996).

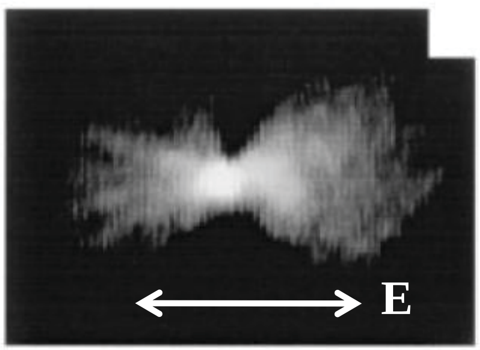


$a << \lambda_0$

$\Downarrow$

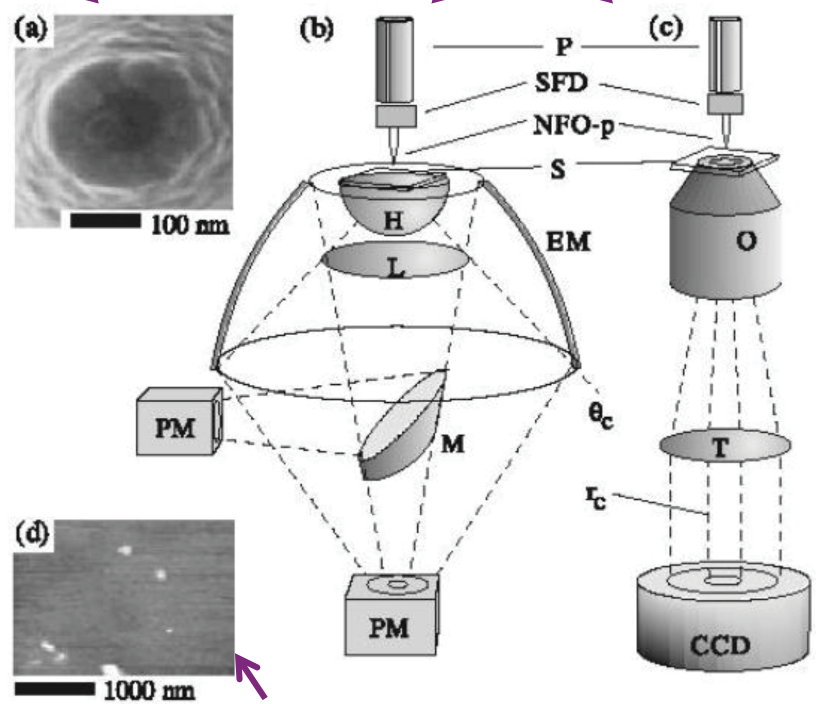
$K > \beta > k_0$

Phase-matching: $k_{\text{SPP}} = k_{\text{inc},x} + K$



probe aperture

two optical setups



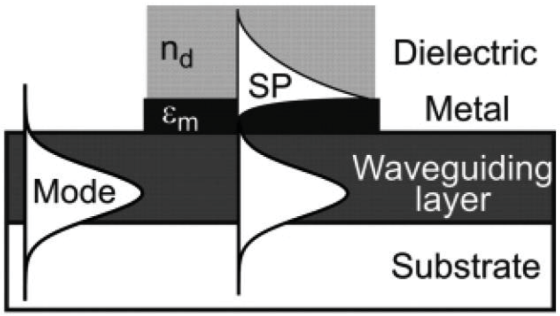
silver film

- Suitable for local SPP excitation
- May act as a nanoscale SPP point source
- Useful for characterizing the effect of surface roughness on SPPs and the scattering at individual surface defects with high spatial resolution

probe: 探针，aperture: 孔径，roughness: 粗糙度，resolution: 分辨率

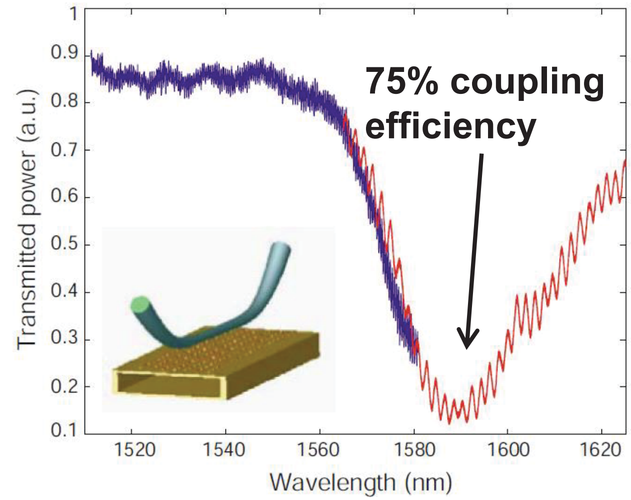
(6) Some other coupling schemes

These are more or less some variations of previous coupling techniques:



Waveguide coupling

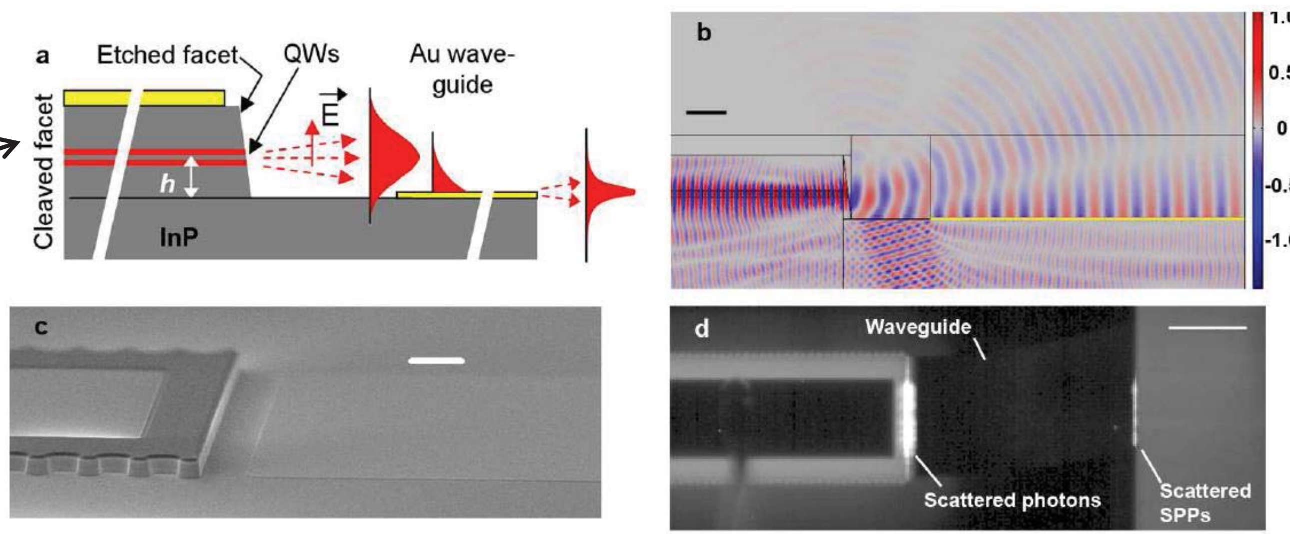
Homola, Chem. Rev. □□□, 462 (2008).



Coupling with optical fiber taper

Maier et al., APL **84**, 3990 (2004).

Laser diode



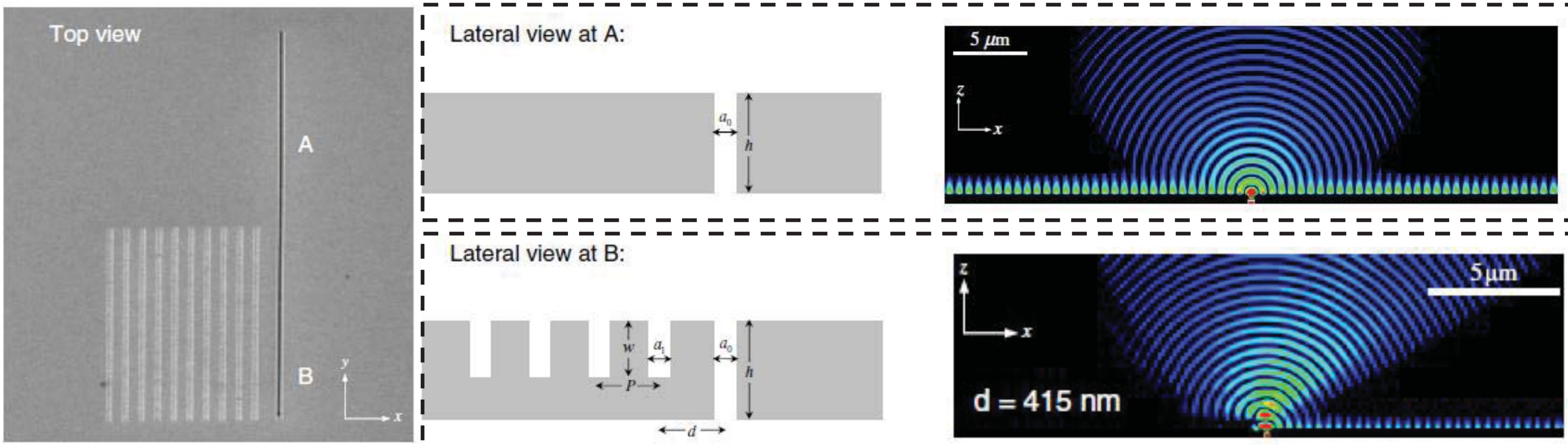
End-fire coupling

Kim et al., Opt. Express **18**, 10609 (2010).

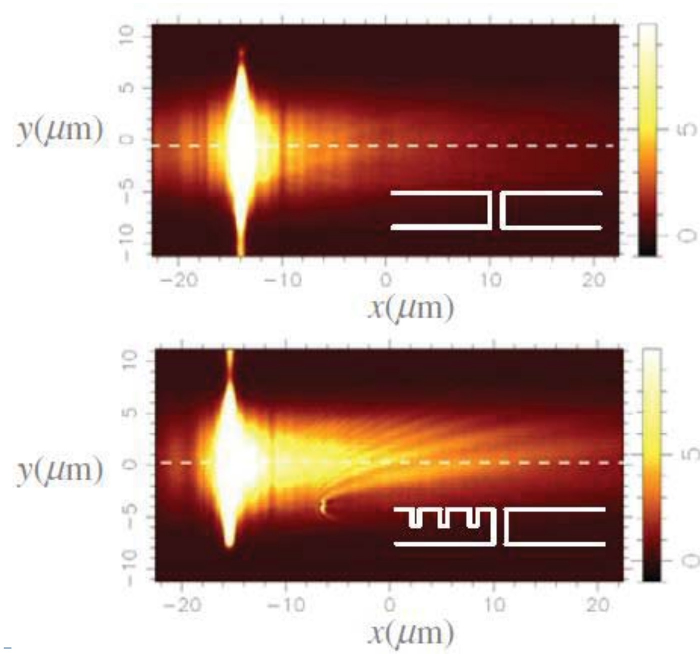
scheme: 方案，variation: 变化，taper: 逐渐变窄的物体，end-fire coupling: 端面耦合

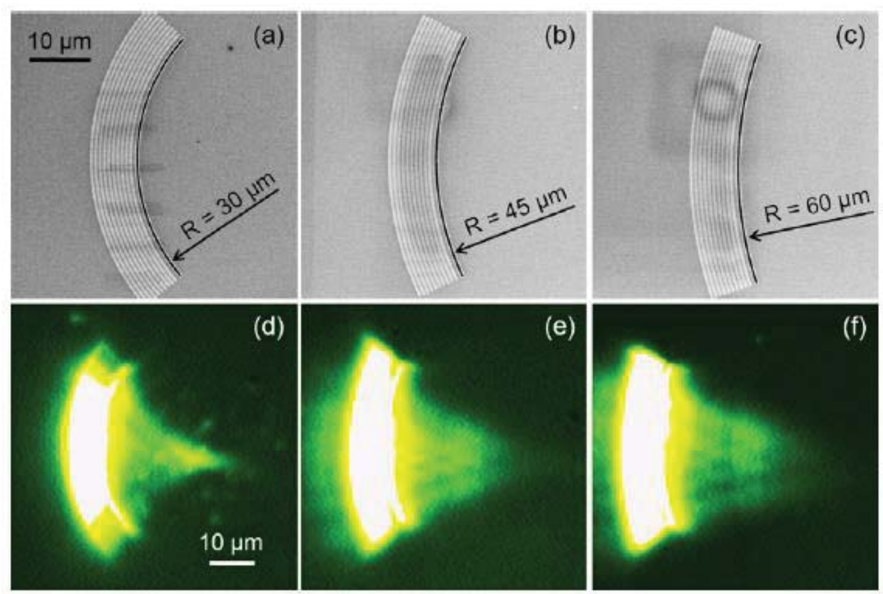
Nanoslit coupling

López-Tejeira et al., New J. Phys. 10, 033035 (2008).



Experiment





slit: 缝

3. Characterization of SPPs

How to see or detect SPPs?

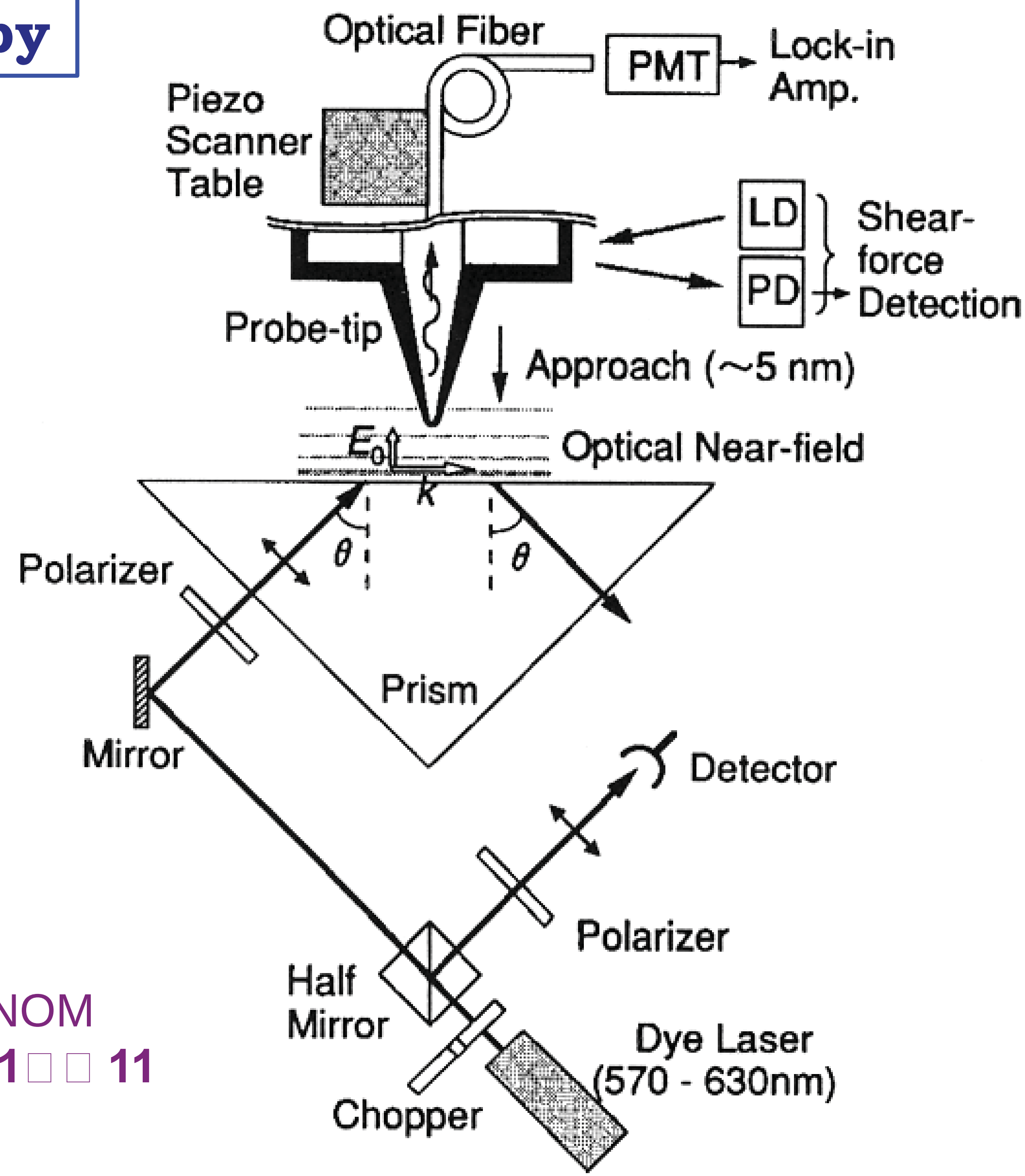
- **Near-field microscopy**
- **Leakage radiation microscopy**
- **Fluorescence imaging**
- **Scattered light imaging**

Commonly used methods

microscopy: 显微术，fluorescence: 荧光

(1) Near-field microscopy

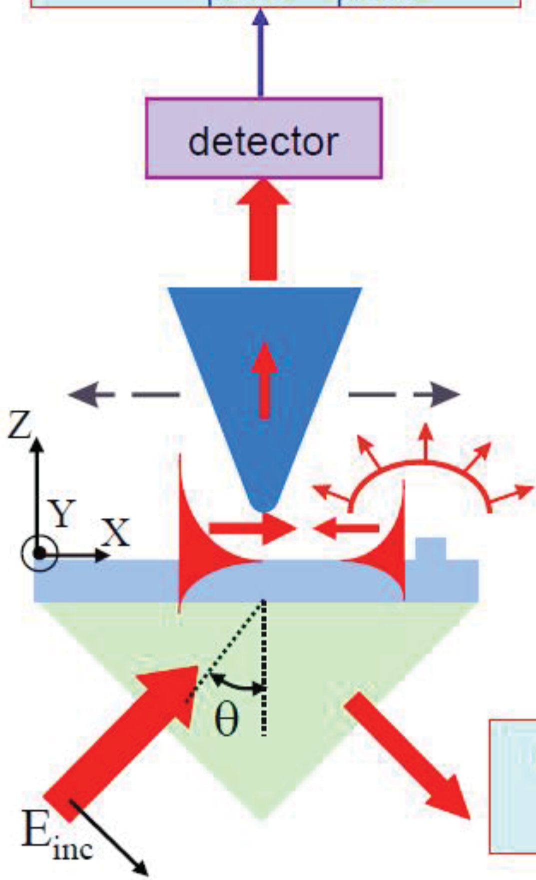
- SPP waves are generated by prism coupling
- Imaging the SPP waves by Scanning Near-field Optical Microscope (SNOM)
- Insert the probe tip to “near field” to convert it to propagating wave
- Near-field optics is essential!



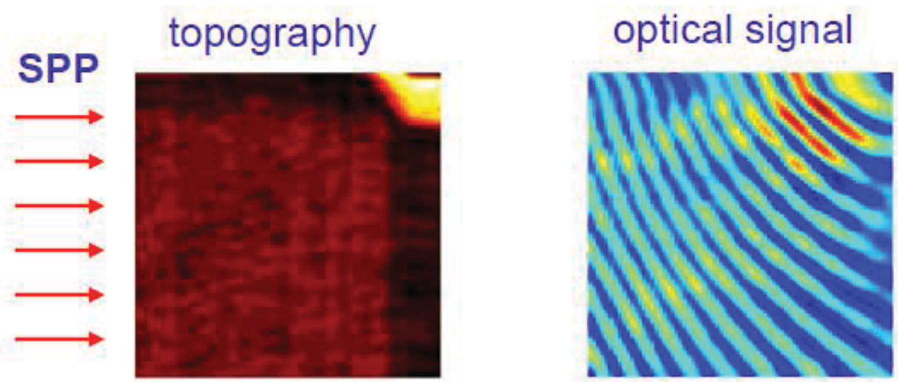
More about near-field optics and SNOM system will be studied in □ec□u□e□1□□ 11

Scanning Near-field Optical Microscope (SNOM): 扫描近场光学显微镜

SNOM optical image:
$S = S(x_{probe}, y_{probe})$



Example: SPP scattering by an individual defect;
45-nm-thick silver film on a glass prism;
λ = 633 nm, p-polarization; image size $3{\times}3\mu m^2$

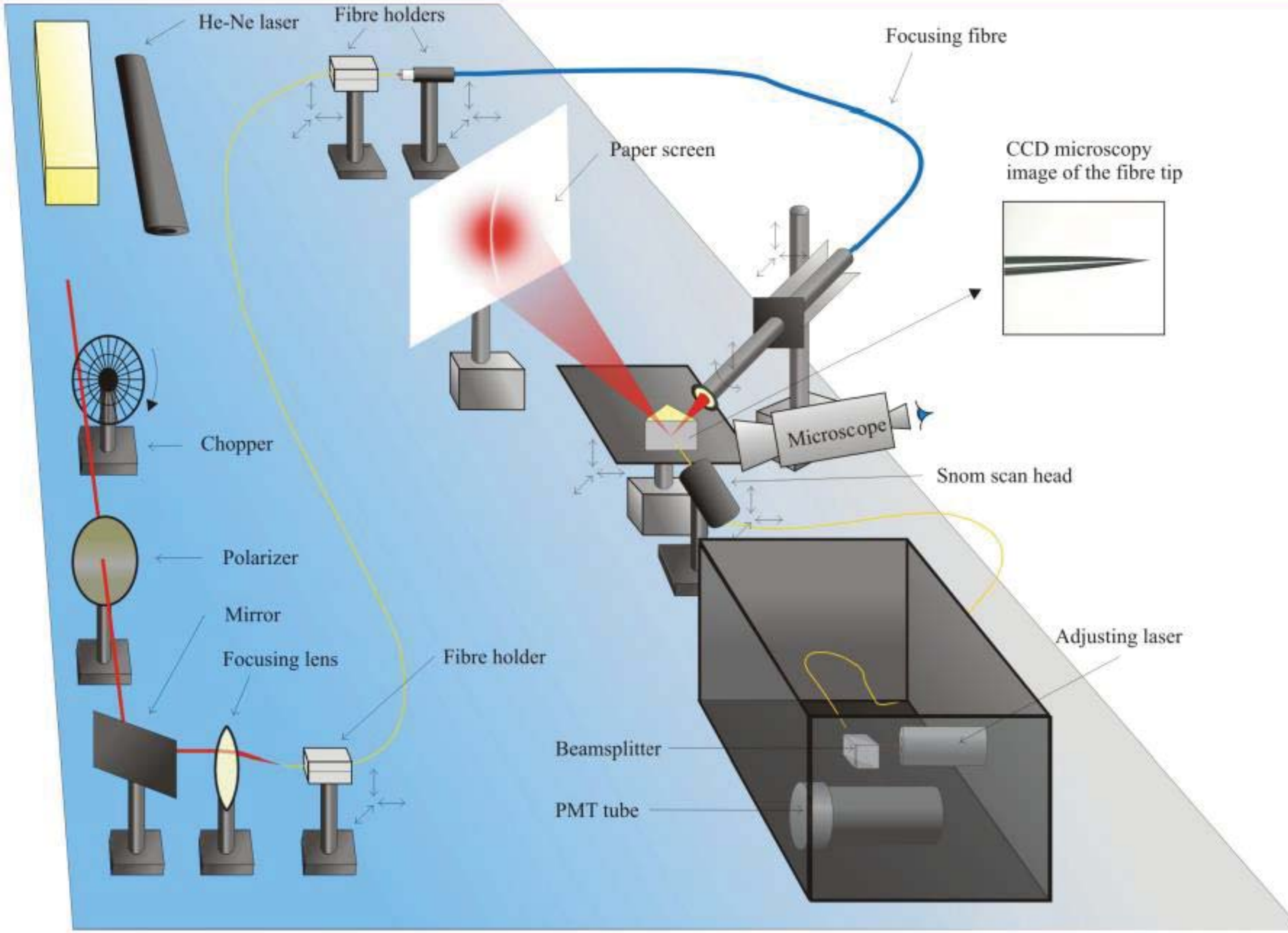


Notice parabolic shape of interference fringes (!)

One should control that the SNOM signal is dominated by the SP contribution (i.e., out-of-plane scattering is weak)!

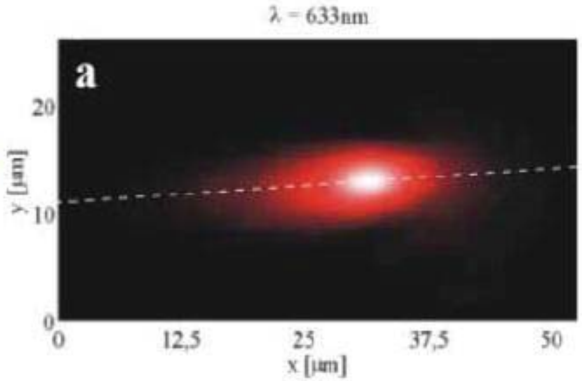
fringe: 条纹

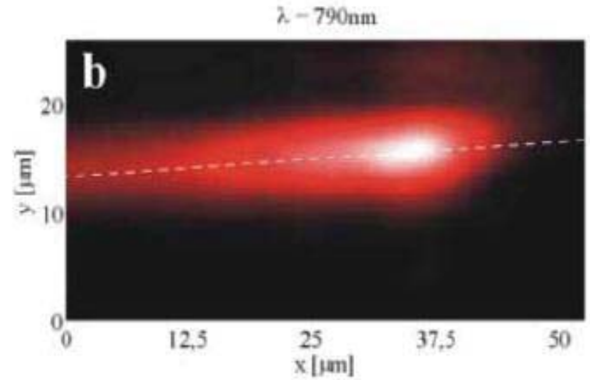
Experimental setup for the **local** SP excitation and SNOM imaging at different wavelengths



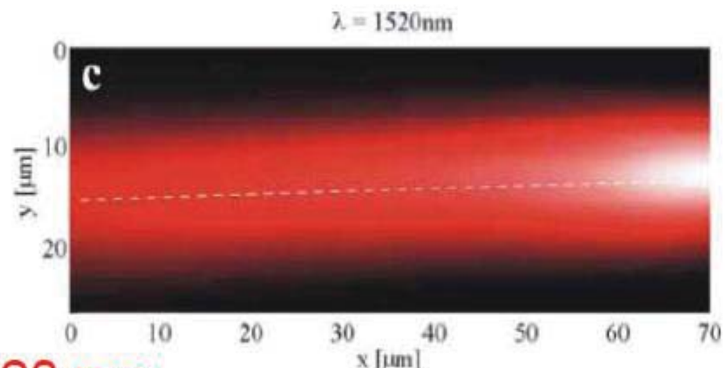
Gold films: direct determination of the SP propagation length at different wavelengths

λ = 633 nm

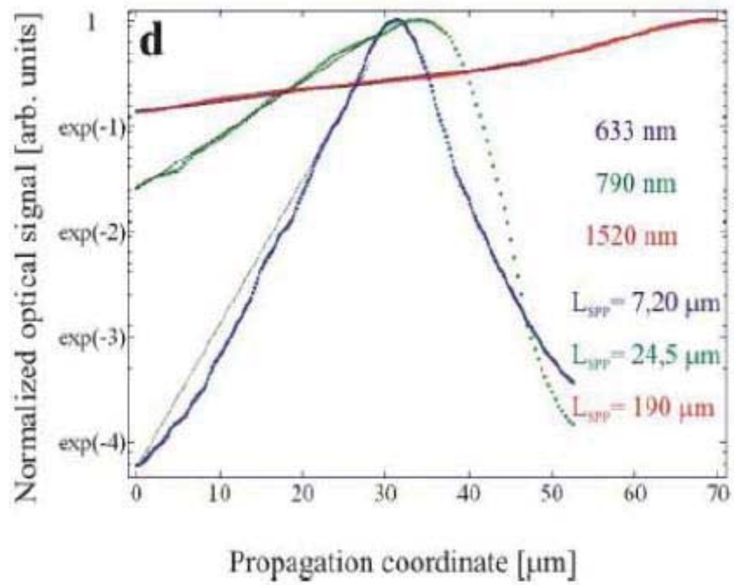




λ = 790 nm

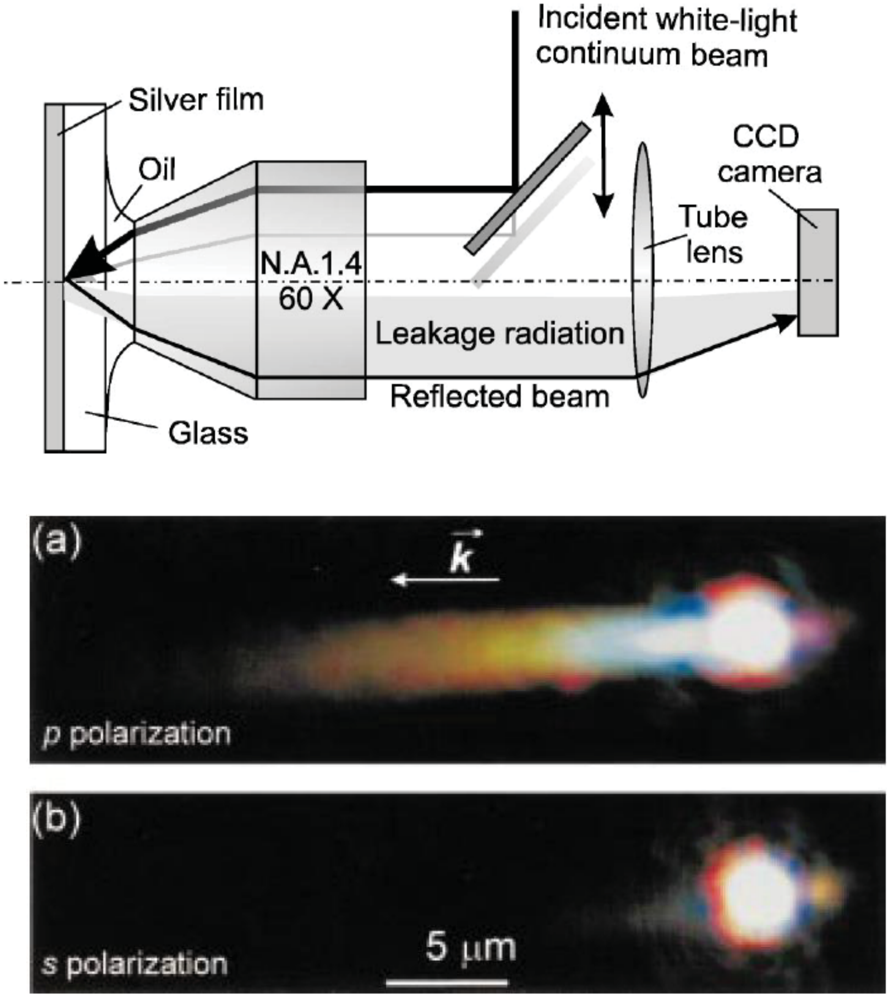


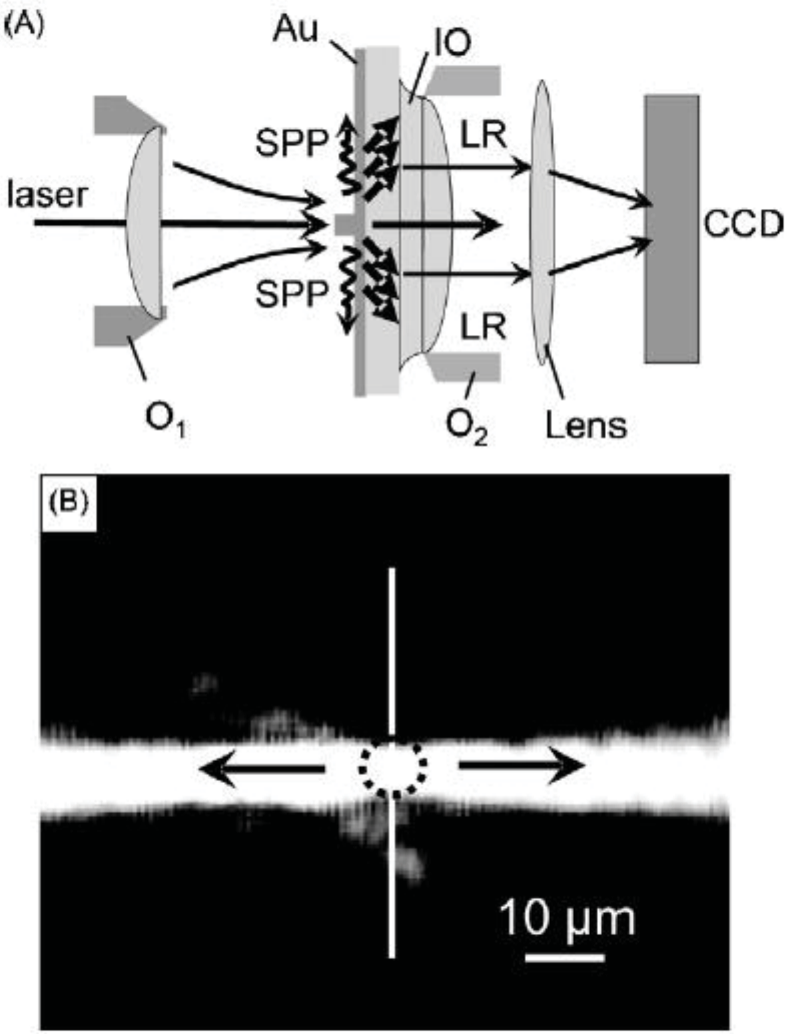
λ = 1520 nm



Opt. Express **13**, 3303 (2005)

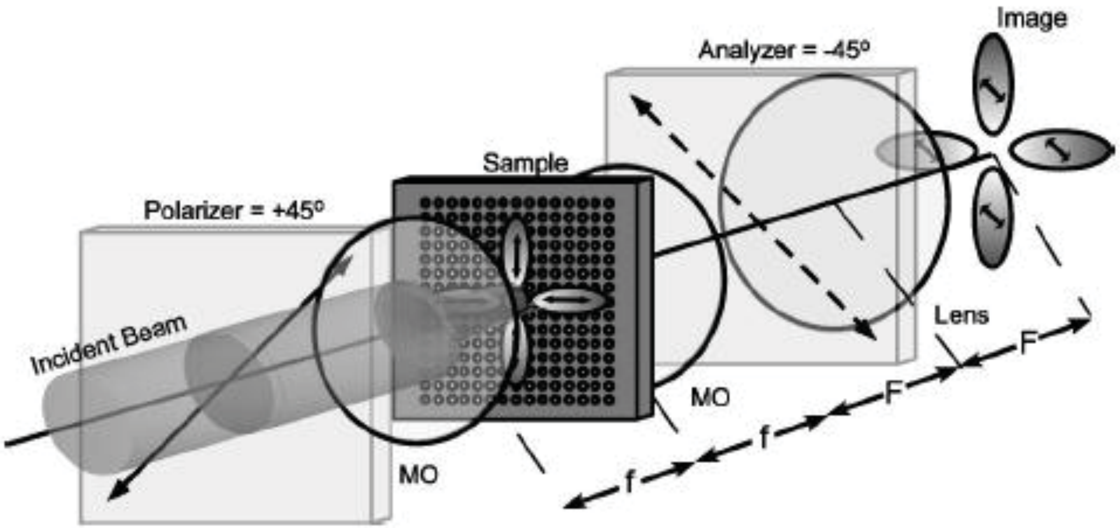
(2) Leakage radiation microscopy





Further reading: Drezet et al., Materials Science and Engineering B **149**, 220 (2008).

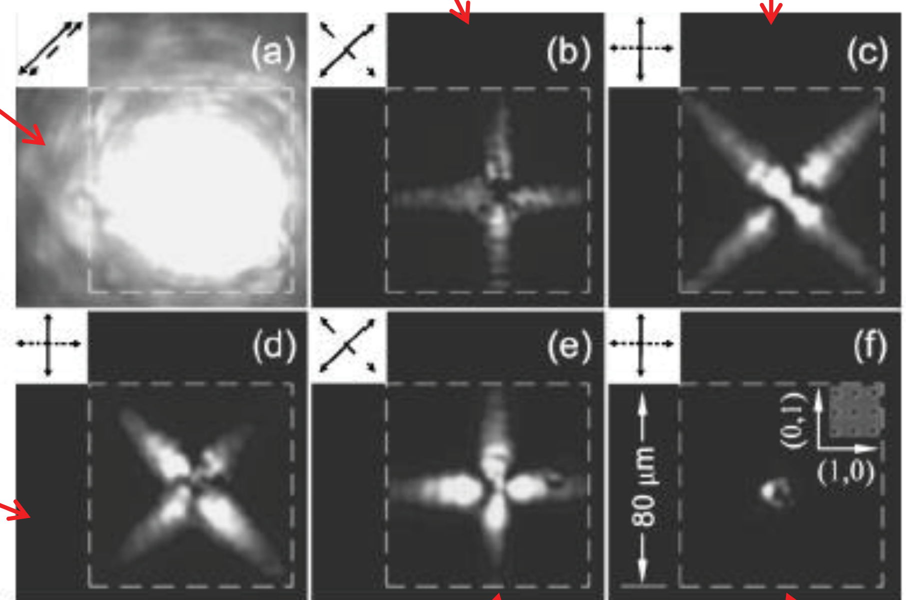
leakage: 泄漏， radiation: 辐射



($\pm$2,0) and
(0,$\pm$2) modes

($\pm$1, $\pm$1)
modes

Directly transmitted
light is not filtered



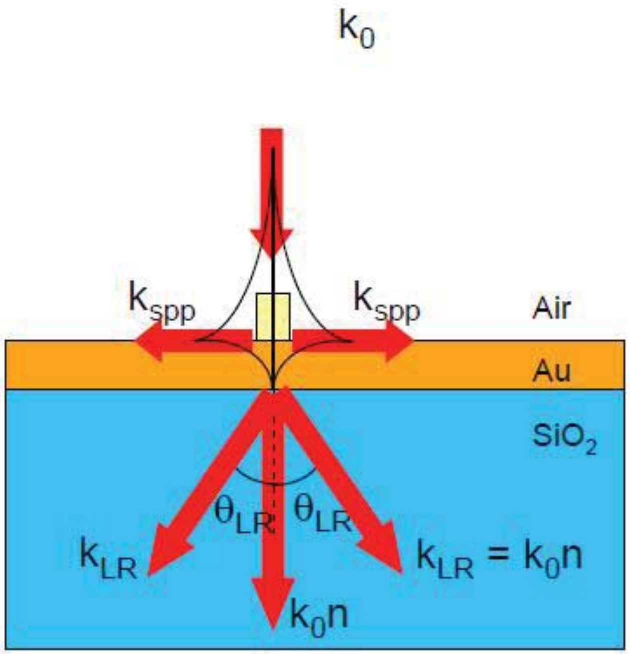
- Direct imaging of SPP modes in a 2D grating

($\pm$1, $\pm$1)
modes

($\pm$1,0) and
(0,$\pm$1) modes

no excitation

Tetz et al., APL **86**, 111110 (2005).



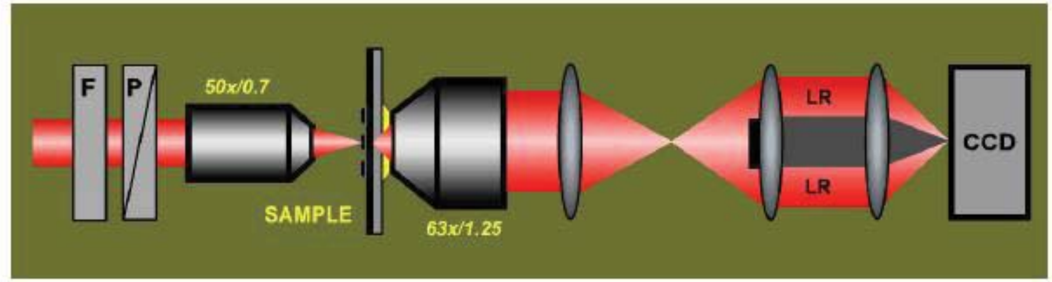
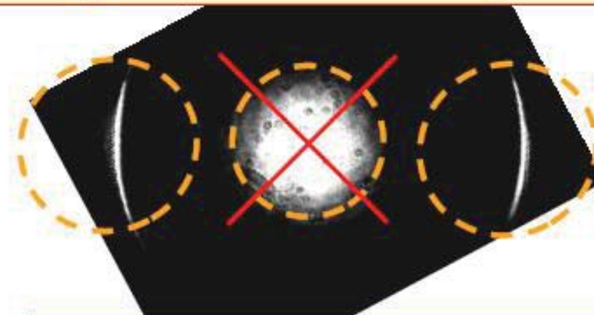
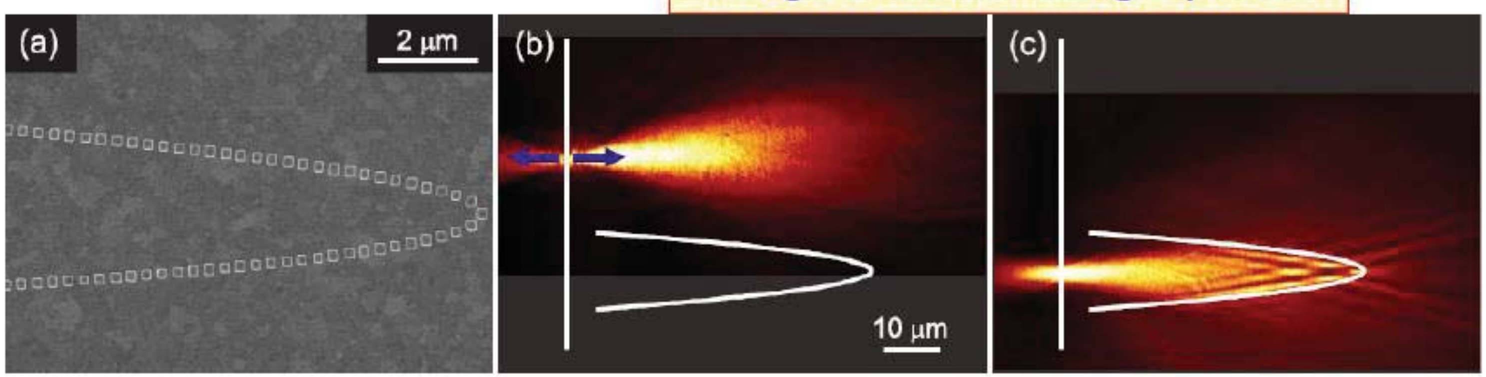


Image in the Fourier plane:

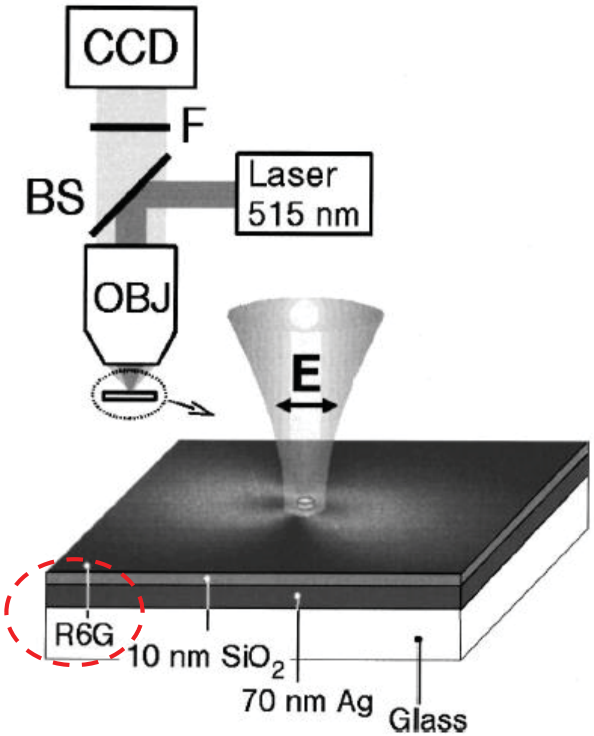


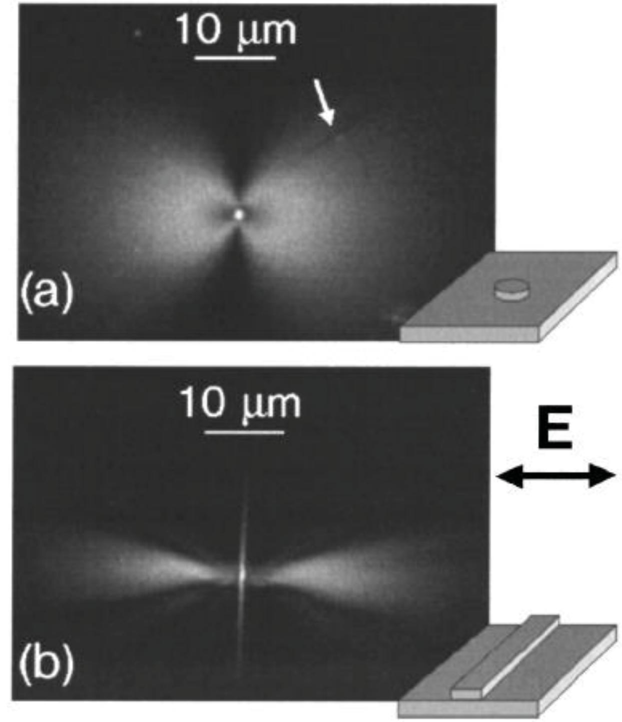
Images in the image plane:



(3) Fluorescence imaging

Ditlbacher et al., APL **8□**, 404 (2002).

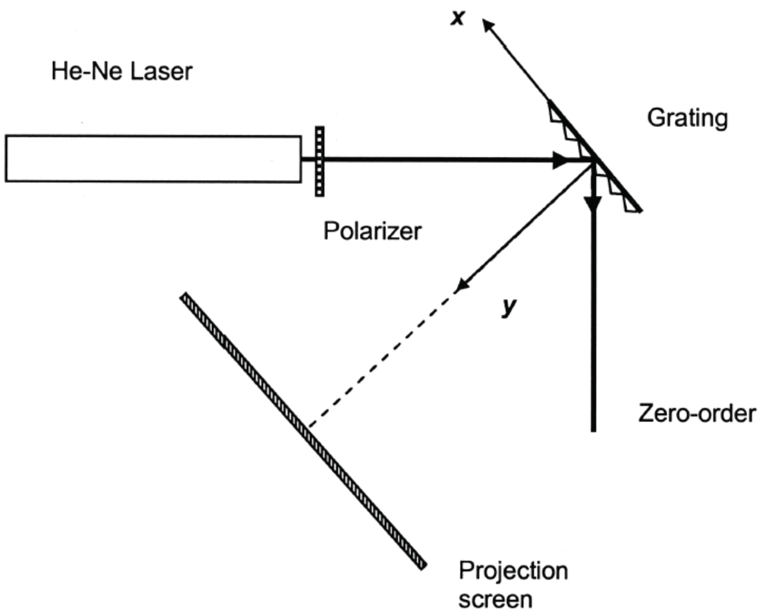




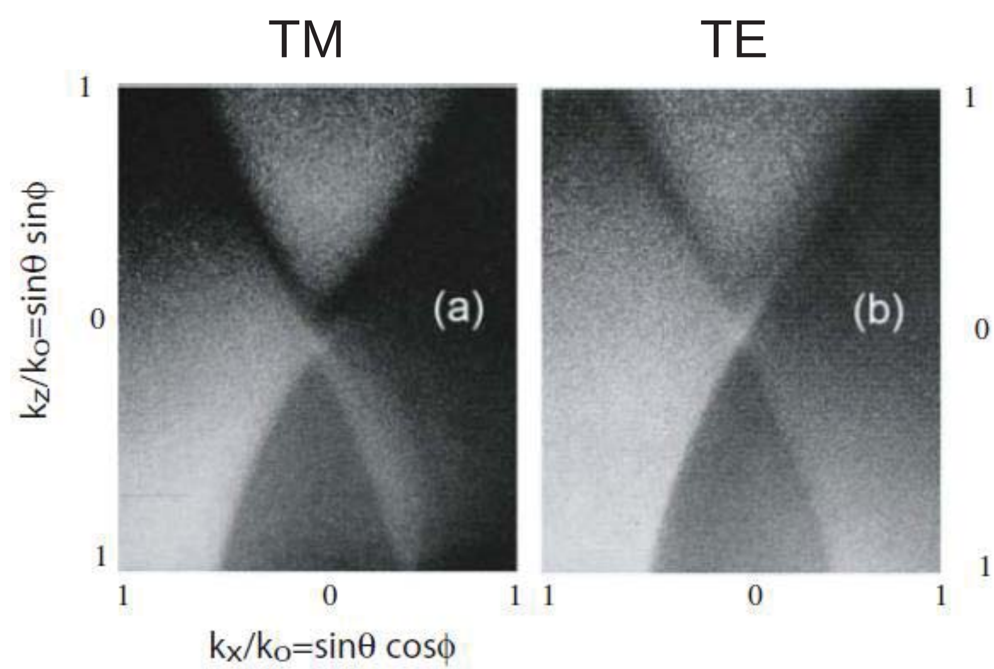
- Rely on the fluorescence of organic molecules placed in the vicinity of the SPP-carrying metal surface
- Fluorescence images have to be recorded within a limited time (typically a few seconds) because of molecule bleaching
- Fluorescence intensity is in general not proportional to the local SPP field intensity → not suitable for quantitative measurement

fluorescence: 荧光，organic: 有机的，vicinity: 附近，bleaching: 漂白，quantitative: 定量的

(4) Scattered light imaging



- SPP propagation is imaged by collecting the light lost to radiation due to scattering at metal surface.
- Surface roughness is important! For high-quality flat surface, scattering is weak.



- Can be used to map out the dispersion relation and band gaps of SPPs on modulated surfaces.

Depine and Ledesma, Opt. Lett. **29**, 2216 (2004).

roughness: 粗糙， modulate: 调制

Summary

- Excitation of SPPs:
  SPPs cannot be excited directly by light on a planar surface;
  Understand the principles and characteristics of different coupling methods:
  - Prism coupling
  - Grating coupling
  - Near-field excitation
  - Excitation by highly focused beam
  - Excitation by scattering
  - Some other coupling schemes
- Characterization of SPPs:
  Four commonly used imaging methods:
  - Near-field microscopy
  - Fluorescence imaging
  - Leakage radiation microscopy
  - Scattered light imaging

  Understand their principles and advantages/disadvantages.