



Nano-Optics

Bert Hecht

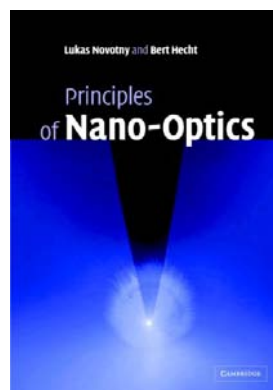
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*Universität Würzburg
Am Hubland
97074 Würzburg*



www.nanoscale-optics.de
→teaching

Literature:



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13. Forces in (nano-)optical fields

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Introduction

- A. Light: an electromagnetic phenomenon
- B. Benefits of optics
- C. Nano Optics
- D. Preview

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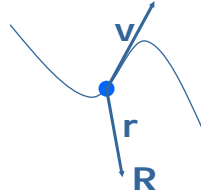
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A. Light as e.m. phenomenon

Fields & moving charges:



Feynman: Lectures on Physics, Volume II, page 406

Liénart-Wiechert potentials:

$$\phi(\mathbf{R}, t) = \frac{q}{4\pi\epsilon_0 [\mathbf{r} - (\mathbf{v} \cdot \mathbf{r}/c)]_{\text{ret}}}$$

$$\mathbf{A}(\mathbf{R}, t) = \frac{q\mathbf{v}}{4\pi\epsilon_0 c^2 [\mathbf{r} - (\mathbf{v} \cdot \mathbf{r}/c)]_{\text{ret}}}$$

$$\mathbf{B} = \nabla \times \mathbf{A} \quad \mathbf{E} = -\nabla\phi - \frac{\partial\mathbf{A}}{\partial t}$$

Quantum picture: _____



Photons:

Momentum: $\hbar\mathbf{k}$

Energy: $h\nu$

Moving charges create electric fields → Creation of light
Electric fields make charges move → Detection of light

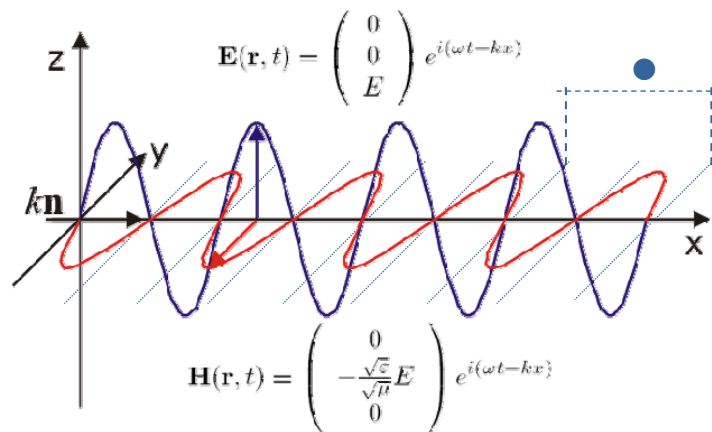
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Plane waves in free space



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Wavelength

Types of e.m. radiation:

- Radio waves (3000 – 0.3 m)
- Micro waves (30 – 0.3 cm)
- Infrared (300 – 1 μm)
- **Visible light: $\lambda = 800 - 350 \text{ nm}$**
- ultraviolet waves: $\lambda = 300 - 30 \text{ nm}$
- x-rays: $\lambda = 30 - 0.03 \text{ nm}$
- γ rays: $\lambda = 0.03 - 0.003 \text{ nm}$

Maxwell's equations are scale invariant
But material parameters vary for different wavelengths

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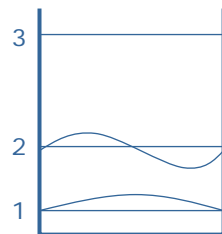
Importance of visible light

Interacts with charges
bound in regions of $\sim 1 \text{ nm}$
characteristic size



Electrons in
larger
molecules

Assume quantum mechanical particle in a box:



$$E_n = \frac{h^2 n^2}{8mL^2}$$

$$E_2 - E_1 = \frac{h^2}{8mL^2} (2^2 - 1^2)$$

$$L = \sqrt{\frac{3h\lambda}{8mc}} \sim 7\text{\AA} \quad \text{for visible light}$$



Photosynthesis, Colour, Vision, ...

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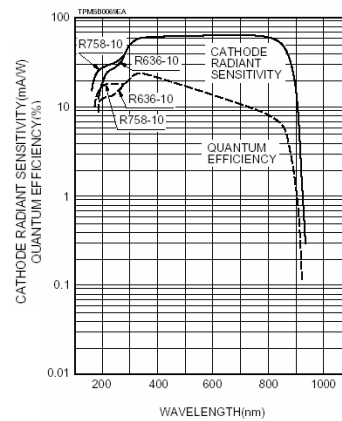
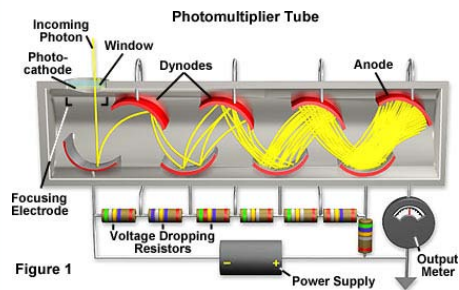
B. Benefits of Optics

- **Sensitivity:** Single photons, single molecules
- **Selectivity:** fluorescence, filters
- **Spectroscopy:** Chemical composition
- **Speed:** fs time resolution (as-pulses)
- **Power**




Sensitivity

Photomultiplier




Dark noise: ~80 counts/s
time resolution 150 ps

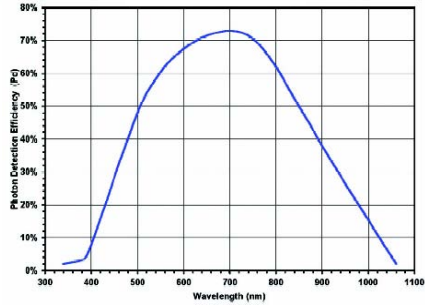
micro.magnet.fsu.edu/primer/

 **Sensitivity**

SPCM



optoelectronics.perkinelmer.com




Dark noise: ~100 counts/s
time resolution ~350 ps


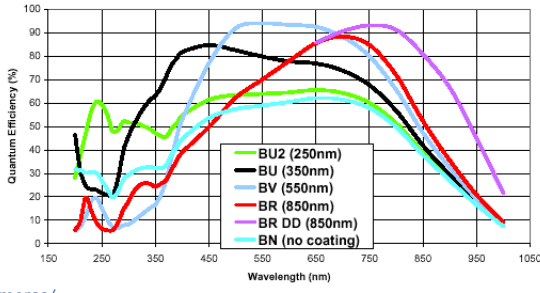
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 **Sensitivity**

CCD

<http://www.andor.com/products/cameras/>

Dark noise: <0.01 counts/s
time resolution ~10 ms

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Selectivity

- Narrow band tunable laser sources

< 1 Mhz line width @ 6×10^{14} Hz

- very high spectral resolution

Filters, monochromators, Fabry-Perot
 ~ 1 nm ~ 0.01 nm < 0.01 nm

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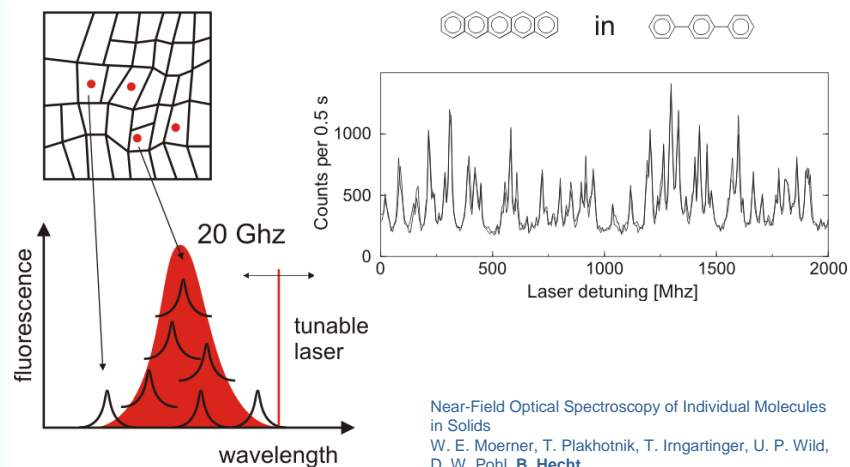
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Selectivity

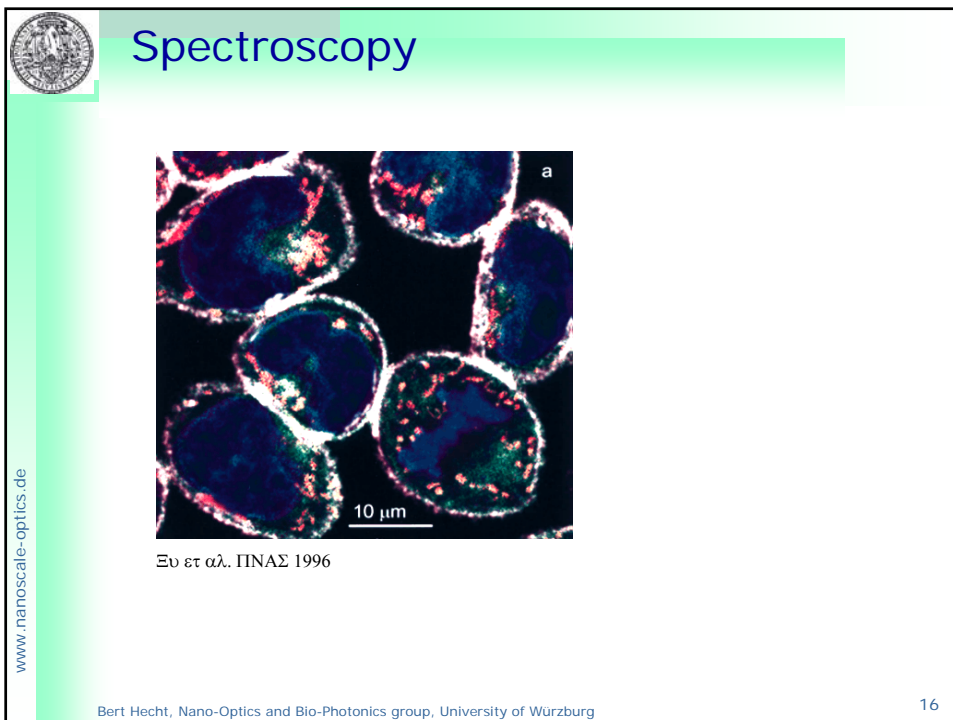
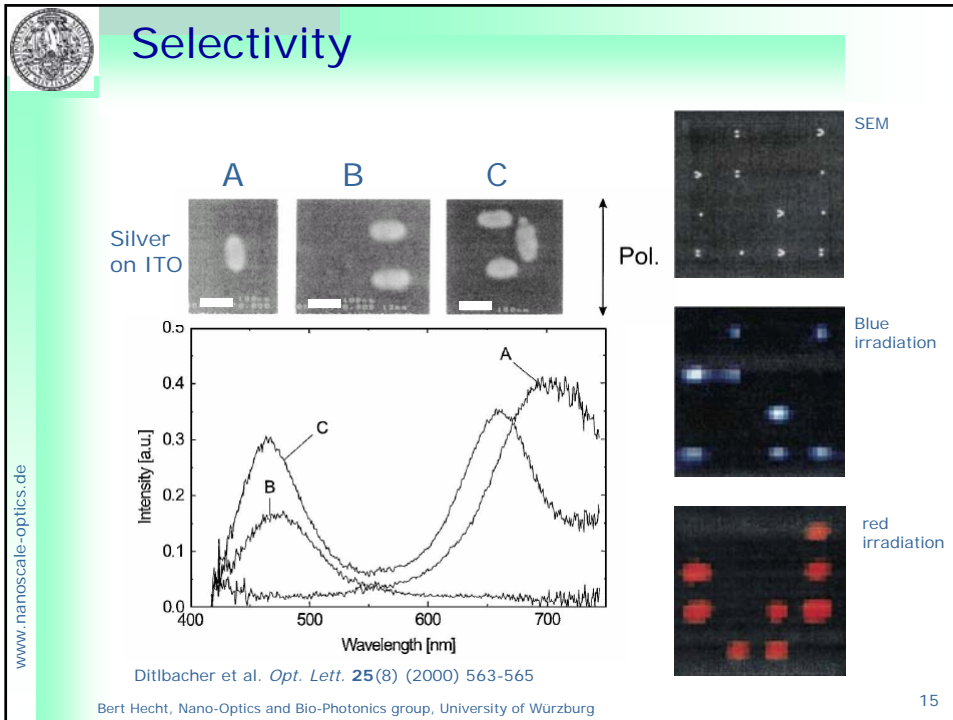
Single-molecule spectroscopy



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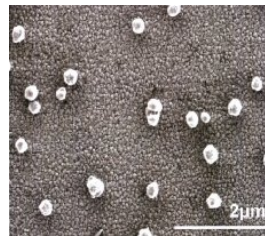
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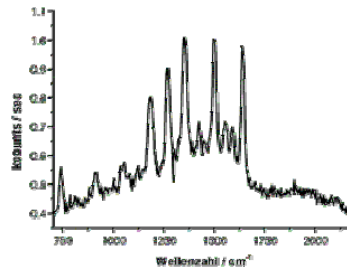


Spectroscopy

Surface enhanced resonance Raman spectroscopy



Silver particles on ITO



SERS spectrum of R6G

www.pc.chemie.uni-siegen.de/pci/

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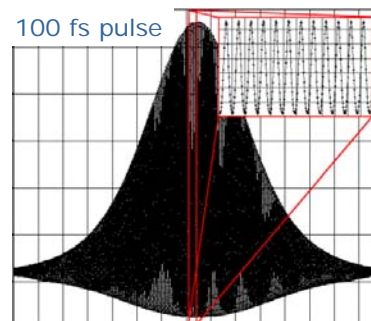
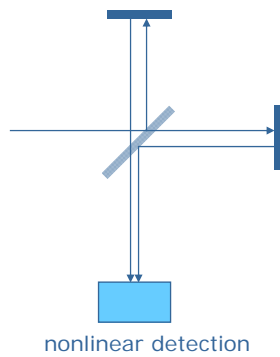
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Speed

fs lasers: 100 fs pulse width is standard

Interferometric autocorrelation:



<http://www.optics.rochester.edu:8080/workgroups/novotny/index.html>

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Experimental nano-control

Brixner et al.
Nature **446**, 301 (2007)

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Speed

Molecular relaxation

frequency

time lag

counts

time [ns]

$(k_r + k_{nr})^{-1}$

molecule A
 $\tau = 4.7 \pm 0.7$ ns

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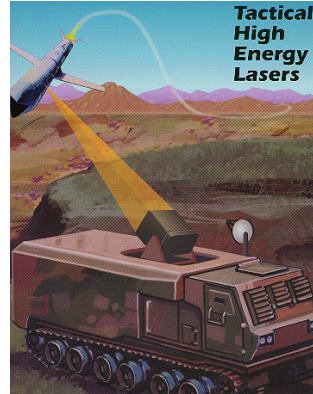


Power

Material processing



www.niagarac.on.ca/study/programs/fulltime/tech0750/career.html



www.usc.edu/dept/materials_science/ccr/research-projects/poster06.htm

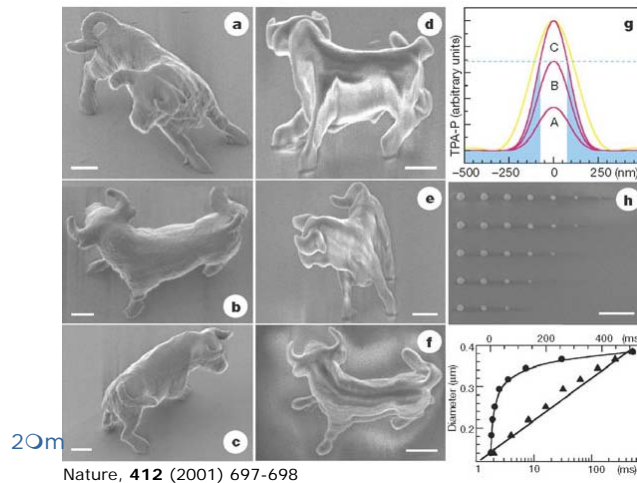
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Power


Finer features for functional micro devices: 2-photon polymerization



Nature, **412** (2001) 697-698

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Spatial resolution is limited by diffraction

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Diffraction limit

Heisenberg: $\Delta x \cdot \Delta p_x \geq \frac{\hbar}{2}$

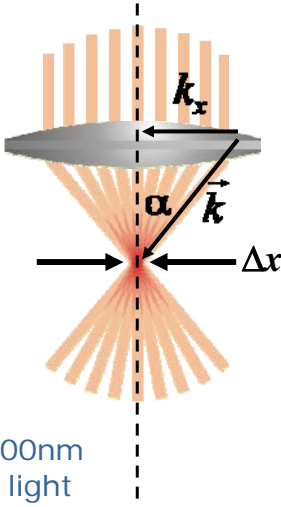
For photons: $\Delta x \cdot \Delta k_x \geq \frac{1}{2}$

$$\Delta x \geq \frac{1}{2nk \sin \alpha} = \frac{\lambda}{4\pi n \sin \alpha}$$

$\Delta x \geq \frac{1.22\lambda}{NA}$

$\Delta x = 200\text{-}300\text{nm}$
for visible light

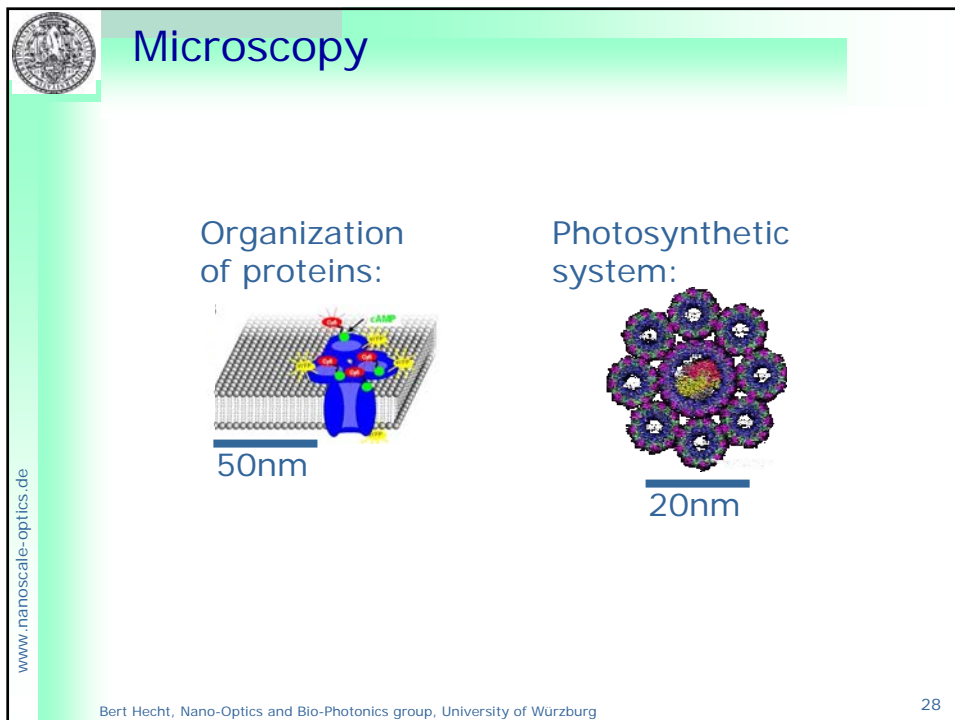
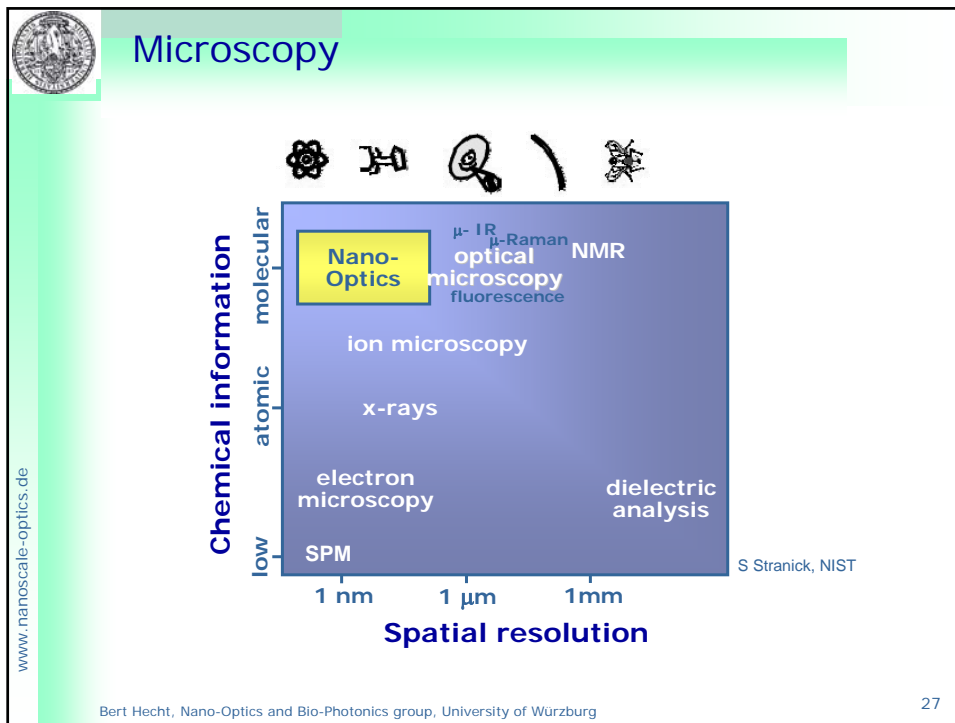
For more detail see e.g. Stelzer & Grill, Opt. Commun. **173**, 51-56 (2000).



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Data storage:

$X\Delta$

• = 780 nm
NA = 0.45

1600 nm

$\Delta\zeta\Delta$

• = 650 nm
NA = 0.6

800 nm

$Y\Delta O$

• = 405 nm
NA = 0.7/0.85

200 nm

<http://www.plasmon.com/>

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Basic principle

$\Delta x \cdot \Delta k_x \geq \frac{1}{2}$

↑
work on this!

Can only be changed dramatically in the vicinity of matter:

$a \ll \lambda$

$k_x^2 + k_y^2 + k_z^2 = k^2 = \frac{2\pi}{\lambda}$

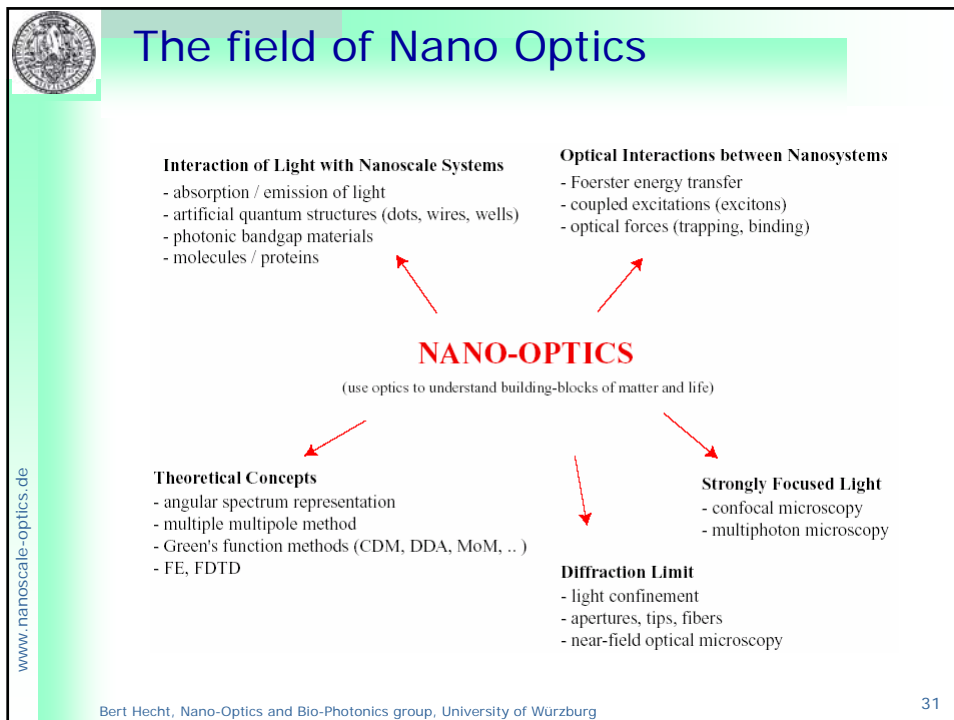
$k_x \sim 1/a \gg k$

$k_z = \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - k_x^2 - k_y^2}$ **imaginary!**

$\Delta x \sim a \ll \lambda$

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Preview

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Classical / "far-field" optics

J. Microscopy 202
(2001) 365-374.

S. Hell and H.K. Stelzer, J.
Opt. Soc. Am. A 9(12)
(1992) 2159-2166


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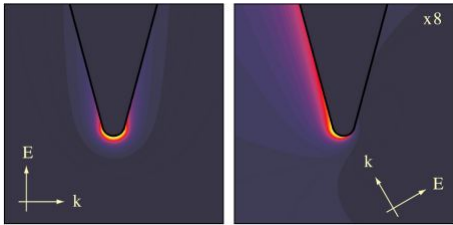
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Aperture SNOM

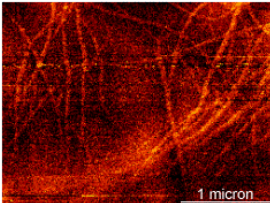
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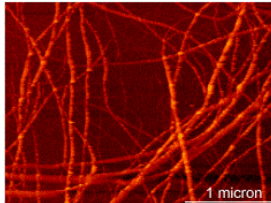
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 **Scattering-type SNOM**


 Left: Schematic of the scattering-type SNOM tip and the electric field (E) and wave vector (k) directions.
 Right: Schematic of the scattering-type SNOM tip and the electric field (E) and wave vector (k) directions, magnified 8 times (x8).

<http://www.optics.rochester.edu:8080/workgroups/novotny/>



 Near-field image (1 micron scale bar)

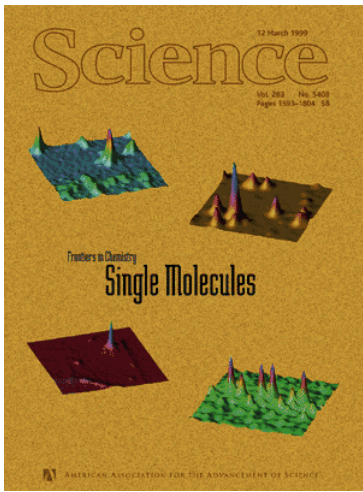

 Topography (1 micron scale bar)

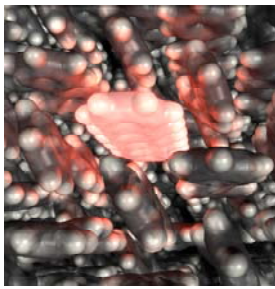
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 **Single-molecule spectroscopy**


 Science journal cover: Frontiers in Chemistry Single Molecules, 12 March 1999, Vol. 283, No. 5408, Pages 1593-1604, 95.
 American Association for the Advancement of Science


 Visualization of a single molecule (credit: A.-S. Bruneau)

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Single-molecule spectroscopy

Tetrahymena ribozyme: a functional RNA molecule

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Ζηρνανη, Ξ. *et al.*
Σχίενηζε **288** (2000)
 2048–2051

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Surface plasmon optics

www.nanoscale-optics.de

A. Bouhelier, Thesis, University of Basel

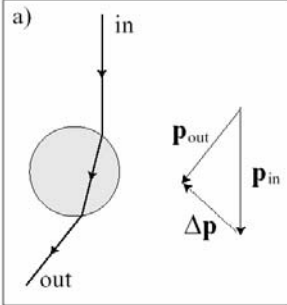
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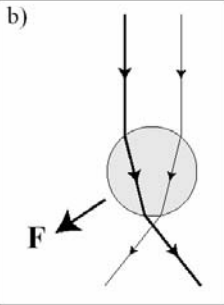


Optical forces

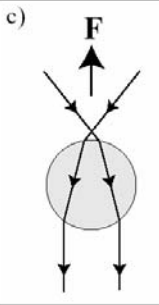
a)



b)



c)




Subwavelength particles?

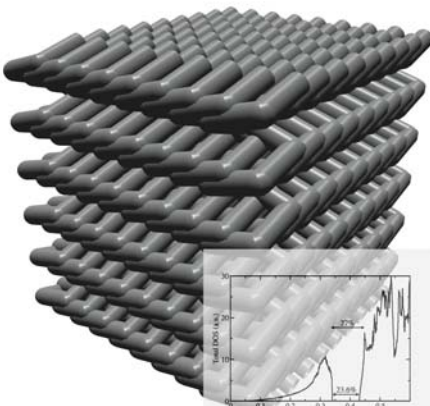
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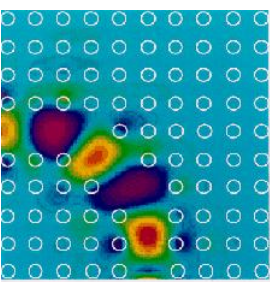
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Photonic structures





J. D. Joannopoulos, R. D. Meade, and J. N. Winn, "Photonic Crystals", Princeton University Press (1995).

www.newsandevents.utoronto.ca/bin2/010510c.asp

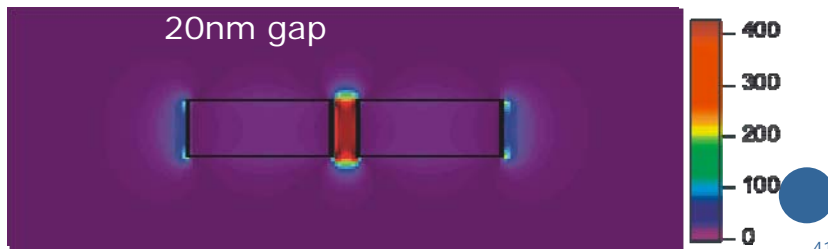
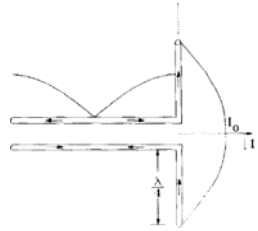
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Optical antenna structures



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