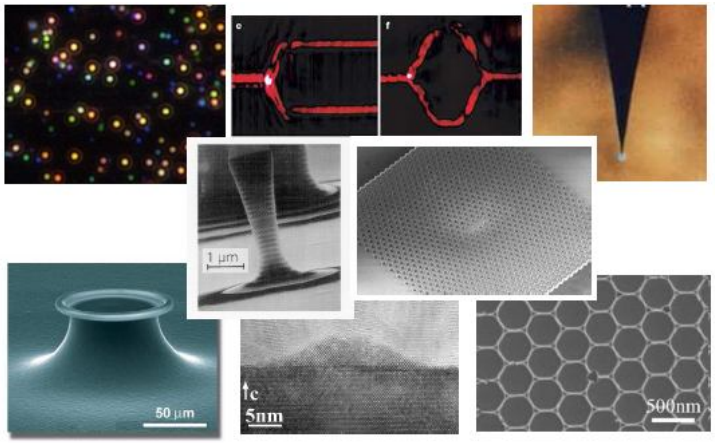
Introduction to Nanophotonics

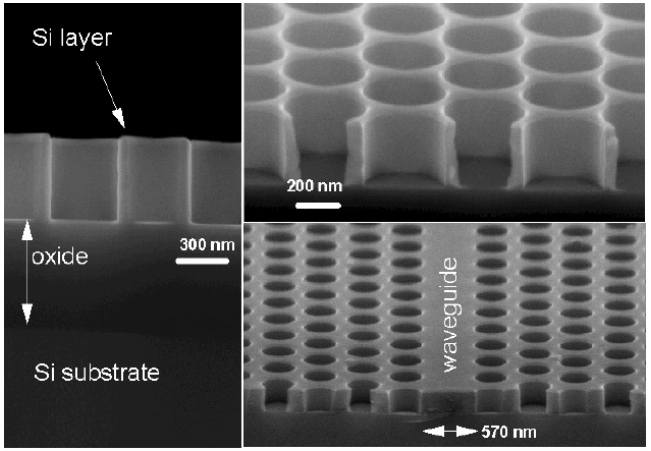
Logan Liu
Micro and Nanotechnology Lab
Department of Electrical & Computer Engineering
University of Illinois

What is Nanophotonics?

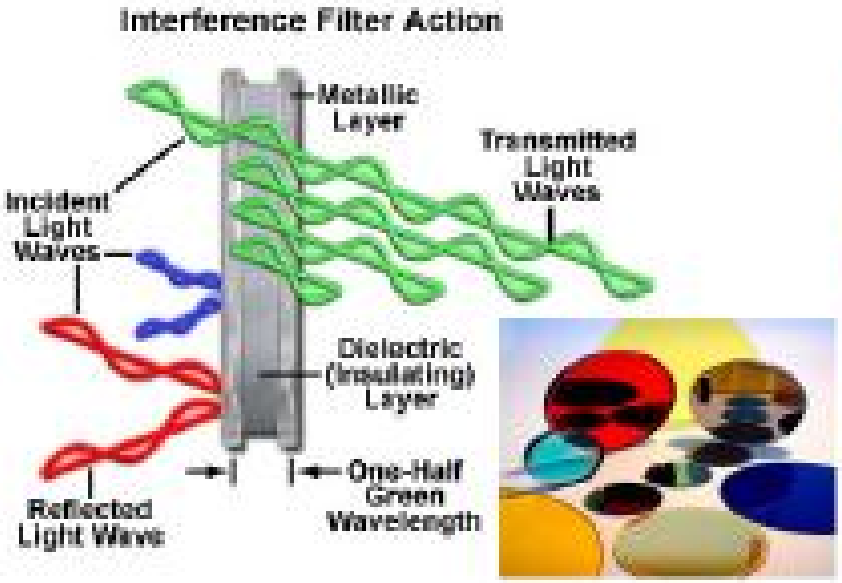
This area of nanoscience, called ***nanophotonics***, *is* defined as "the science and engineering of light matter interactions that take place on wavelength and subwavelength scales where the physical, chemical or structural nature of natural or artificial nanostructured matter controls the interactions"

---National Academy of Science



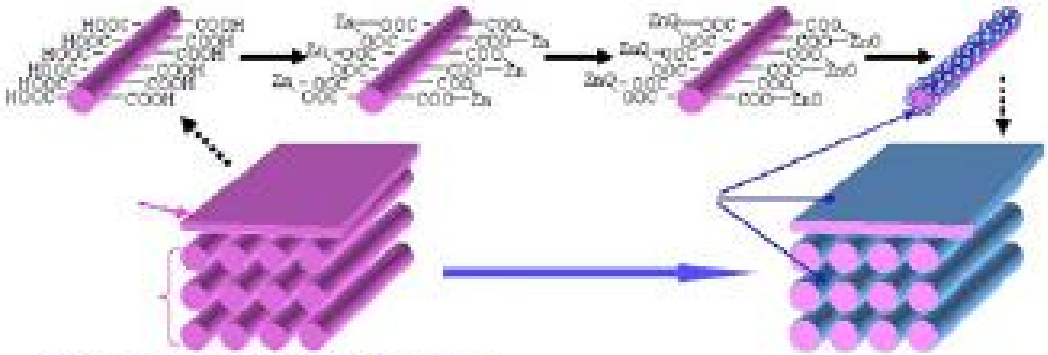


Early Examples of Nanophotonics



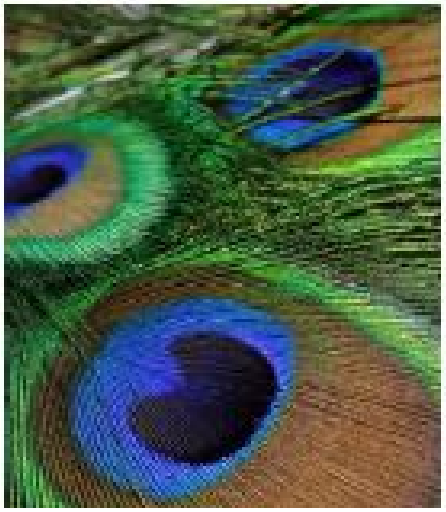
Nanophotonics in Mother Nature

Feathers

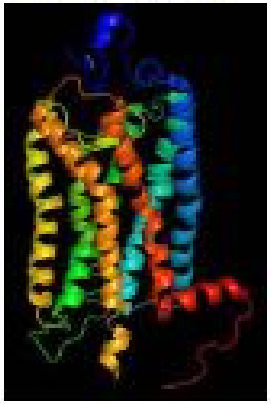


ZnO nanoparticles in peacock feathers

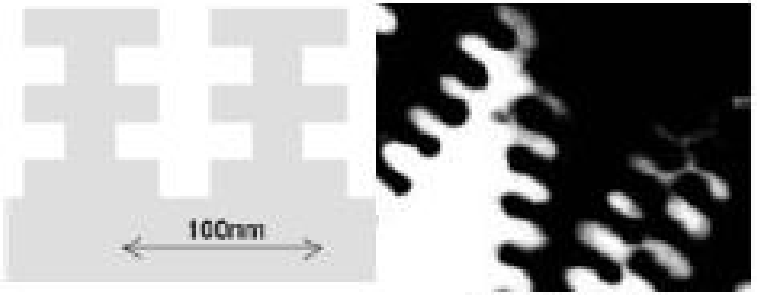
Zhang, Nanotechnology 2008



Photoreceptor rhodopsin



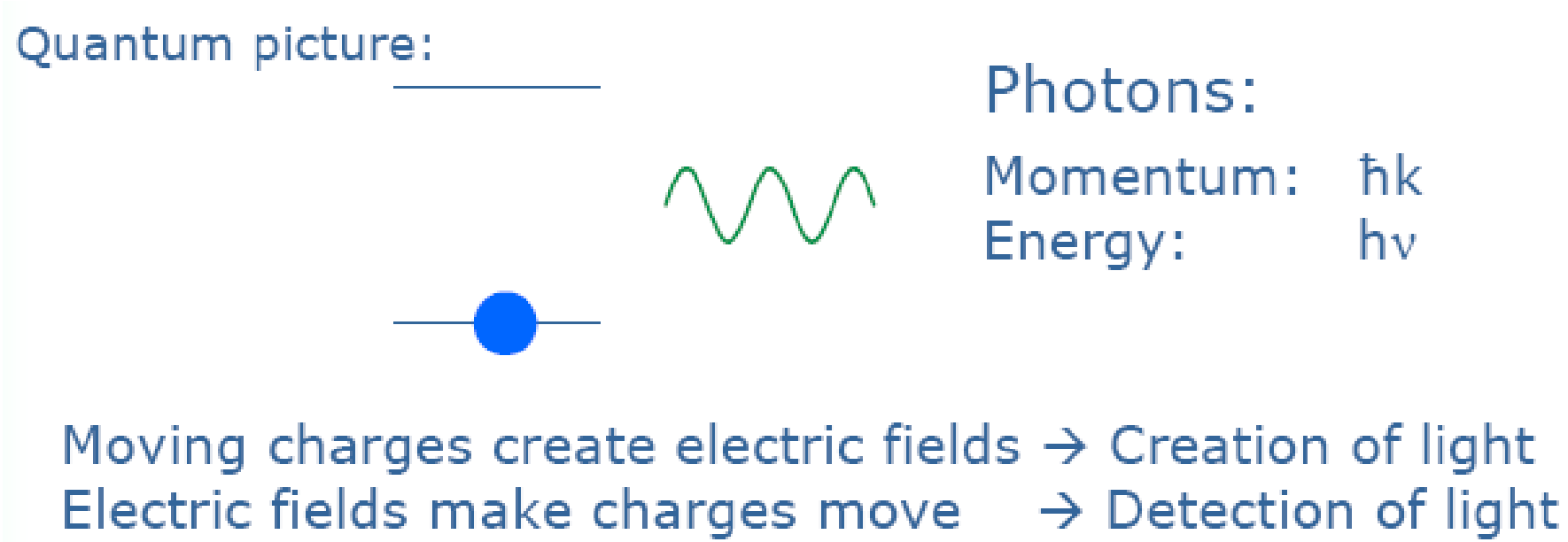
Butterfly wings



Courtesy: Onera

Foundation of Nanophotonics

- Photon-Electron Interaction and Similarity



"There's Plenty of Room at the Bottom" (Feynman, 1961)

Foundation of Nanophotonics

Basic Equations describing propagation of photons in dielectrics has some similarities to propagation of electrons in crystals

Similarities between Photons and Electrons

Wavelength of Light, $\lambda = \frac{h}{p} = \frac{c}{\nu}$

Wavelength of Electrons, $\lambda = \frac{h}{p} = \frac{h}{mv}$

Foundation of Nanophotonics

Maxwell's Equations for Light

$$\nabla \times H = \frac{1}{c}\frac{\partial D}{\partial t} \qquad \nabla \times E = \frac{-1}{c}\frac{\partial B}{\partial t}$$

Eigenvalue Wave Equation:

$$\nabla \times [\mu^{-1} \nabla \times E(r)] = \omega^2 \varepsilon E(r)$$

$$\nabla \times [\varepsilon^{-1} \nabla \times H(r)] = \omega^2 \mu H(r)$$

For plane wave $\nabla \cdot \nabla E(r) = \varepsilon k_0^{\,2} E(r)$

Describes the allowed frequencies of light

Schrodinger's Eigenvalue Equation for Electrons:

$$\frac{-(\frac{h^2}{4\pi^2})}{2m}[\nabla \cdot \nabla + V(r)]\psi(r) = E\psi(r)$$

Describes allowed Energies of Electrons

Foundation of Nanophotonics

Free Space Solutions:

Photon Plane Wave: $$E = E^0\left(e^{ik.r-\omega t} + e^{-ik.r+\omega t}\right)$$

Electron Plane Wave: $$\psi = c\left(e^{ik.r-\omega t} + e^{-ik.r+\omega t}\right)$$

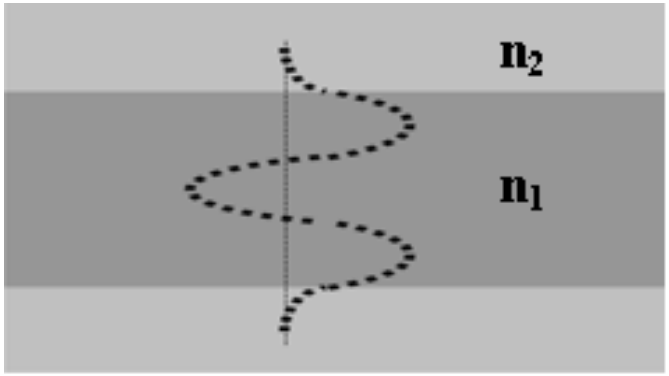
Interaction Potential in a Medium:

Propagation of Light affected by the Dielectric Medium (refractive index)

Propagation of Electrons affected by Coulomb Potential

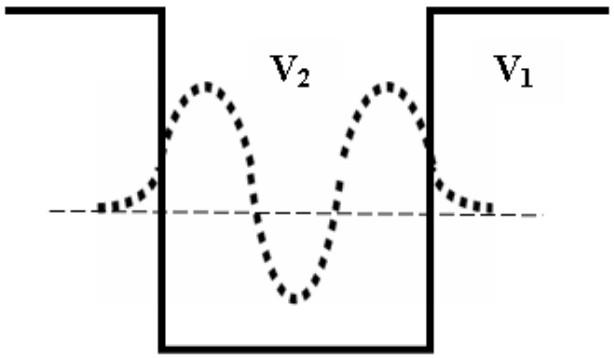
Foundation of Nanophotonics

Photon tunneling through classically forbidden zones. E and B fields decay exponentially. k-vector imaginary.



Planar Waveguide, $n_1 > n_2$

Electron Wavefunction decays exponentially in forbidden zones



$V_1 > V_2$

Wavefunction for a particle in a Potential Well

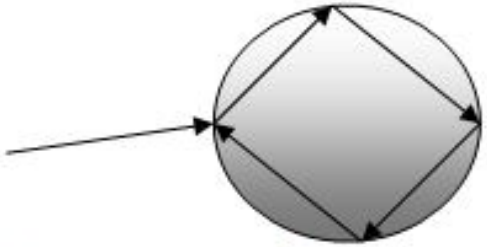
Foundation of Nanophotonics

Confinement of Light results in field variations similar to the confinement of Electron in a Potential Well. For Light, the analogue of a Potential Well is a region of high refractive-index bounded by a region of lower refractive-index.

Microscale Confinement of Light

Planar Waveguide 1-D Confinement

Optical fiber: 2-D Confinement



Microsphere: 3-D Confinement

Nanoscale Confinement of Electrons

Thin film-Quantum Well
1 D Confinement

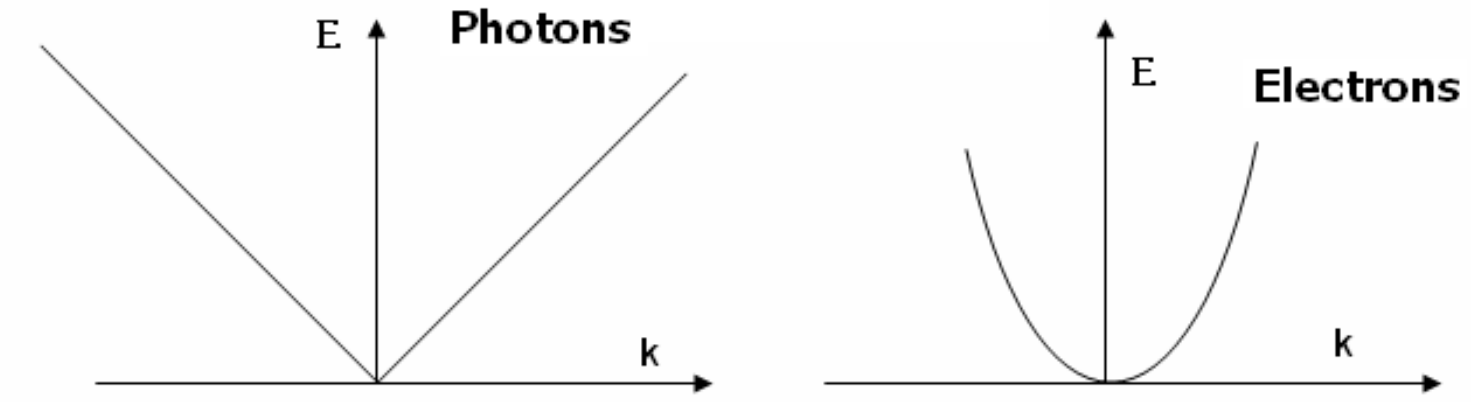
Quantum Wire: 2-D Confinement

Quantum Dot: 3-D Confinement

Foundation of Nanophotonics

- Free space propagation of both electrons and photons can be described by Plane Waves.
- Momentum for both electrons and photons, $\mathbf{p} = (h/2\pi)\mathbf{k}$
- For Photons, $k = (2\pi/\lambda)$ while for Electrons, $k = (2\pi/h)mv$
- For Photons, Energy $E = pc = (h/2\pi)kc$ while for Electrons,

$$E = p^2/2m = (h/2\pi)^2 k^2/2m$$

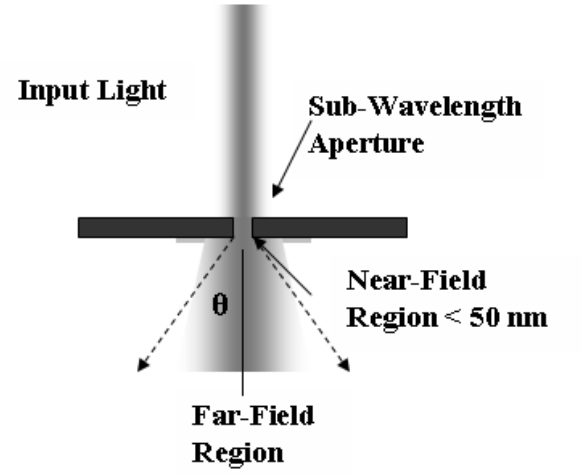


Free Space Dispersion for Photons and Electrons

Near Field Optics

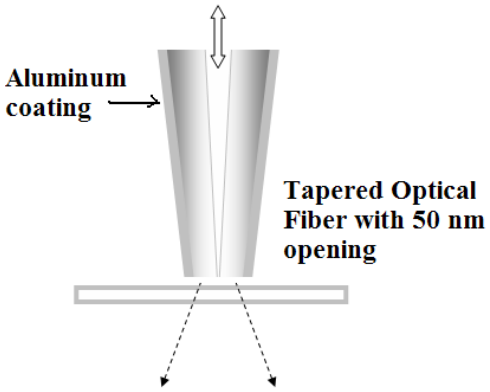
In Far-Field Microscopy, $\text{Re}\,solution = 1.22\left(\frac{\lambda}{2NA}\right)$

This can be overcome with Near-Field Techniques by having nanoscale apertures or by using aperture-less techniques which enhance light interaction over nanoscale dimensions with the use of nanoscale tips, nanospheres etc. The idea of using sub-wavelength aperture to improve optical resolution was first proposed by Synge in a letter to Einstein in 1928. These ideas were implemented into optics much later in 1972 [Ash and Nicholls]

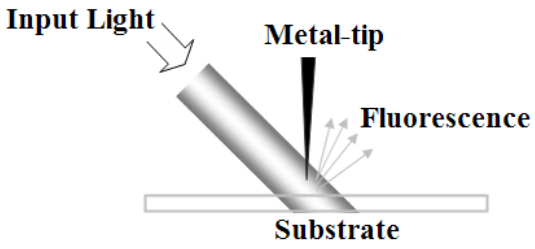


Near-field light decays over a distance of 50 nm from aperture.

Schematic set-ups for Near-Field Scanning Optical Microscope (NSOM)



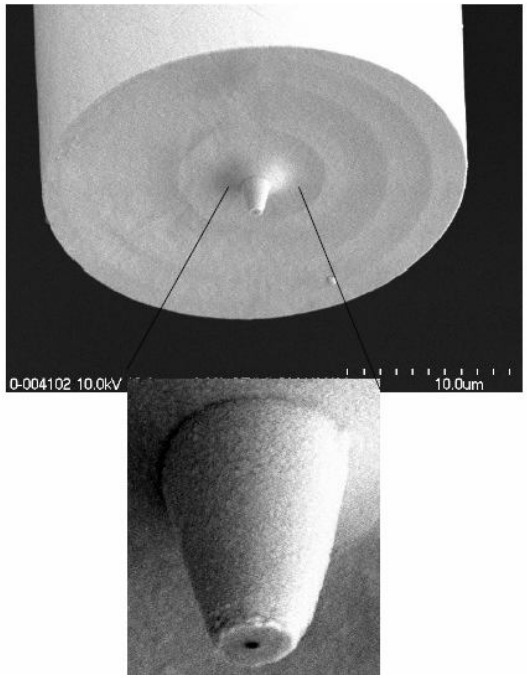
Tapered Optical-Fiber

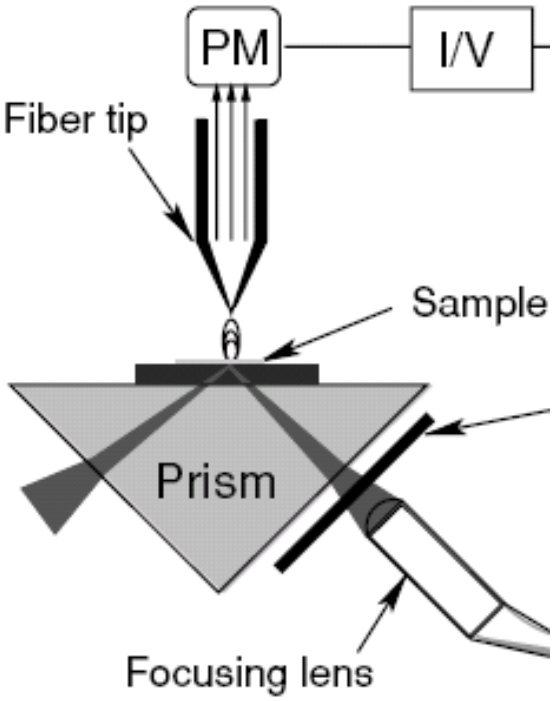


Aperture-less Technique: Near-Field around Nano-Tip

Near-Field Optics

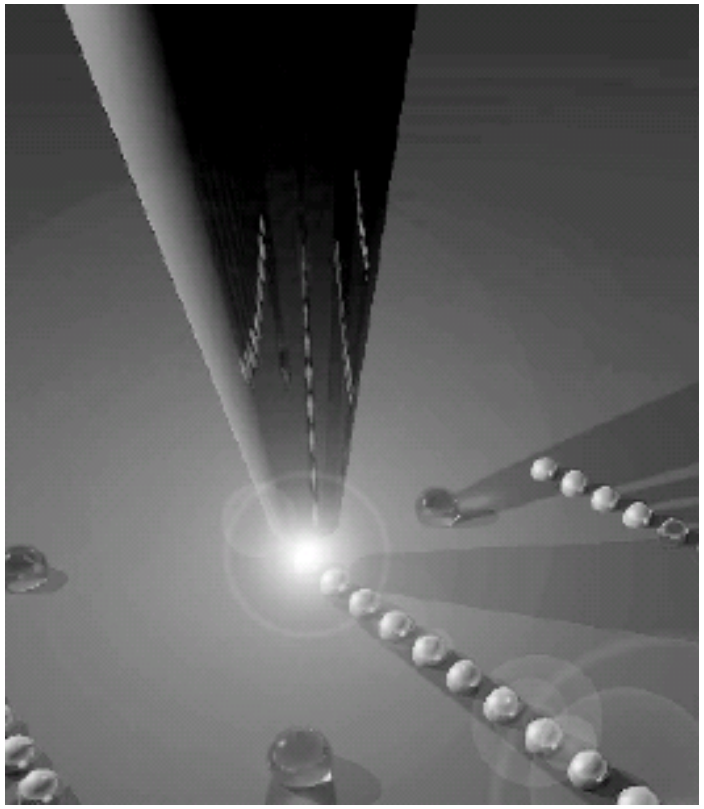
PSTM





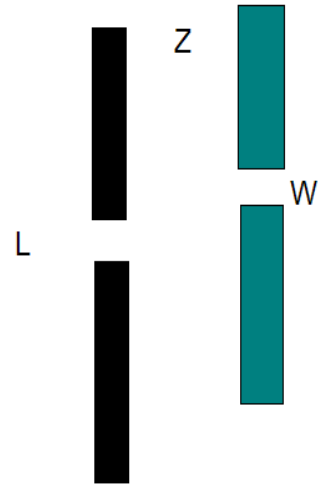
Tip collects the evanescent light created by laser illuminating the sample from the back

SNOM



Tip illuminates the sample; Scattered light is collected

Near Field Optics



Model of far- or near-field, Left:
Slit,illuminated with plane wave
Right: sub-wacelength aperture.

(Paesler, <Near-field Optics>)

$$f(x, z=Z) = \int_{-\infty}^{+\infty} d\alpha_x e^{-i2\pi\alpha_x x} F(\alpha_x, z=0) e^{-i2\pi(\alpha^2-\alpha_x^2)^{1/2} Z} \quad \cdots\cdots(1)$$

For far field only need to integrate over $|k| \le \omega / c$, i.e.

$$f(x, z=Z) = \int_{-\frac{\omega}{2\pi C}}^{+\frac{\omega}{2\pi C}} d\alpha_x e^{-i2\pi\alpha_x x} F(\alpha_x, z=0) e^{-i2\pi(\alpha^2-\alpha_x^2)^{1/2} Z} \cdots(2)$$

$z = \varepsilon << \lambda$, Then Eqn. (1) is recaptured by $Z \to \varepsilon$

Then taking at aperture, $f(x, z=\varepsilon) = rect(x/\omega)$

Now far field: $f(x, z=Z) = \int_{-\frac{\omega}{2\pi C}}^{\frac{\omega}{2\pi C}} d\alpha_x \{ e^{-i2\pi\alpha_x x} e^{-i2\pi\sqrt{\alpha^2-\alpha_x^2}(Z-\varepsilon)} \times$

$$\int_{-\infty}^{\infty} d\alpha_x'' e^{-i2\pi\alpha_x'' x} F(\alpha_x'', z=0) \frac{\sin((\alpha_x - \alpha_x'')w)}{\alpha_x - \alpha_x''} \cdot e^{-2\pi\sqrt{\alpha^2-\alpha_x''^2}\varepsilon} \} \cdots(3)$$

$F(\alpha_x, z=0) = E_o \delta(\alpha_x - K)$, with K one spatial frequency

Near Field Optics

Continued from the previous page

$$Eqn.(1) \Rightarrow f(x, z = Z) = E_o e^{-i2\pi Kx} \cdot e^{-i2\pi\sqrt{\alpha^2 - K^2}Z} \qquad \text{for } K < \omega / C$$

$$= 0, \qquad \text{for } K > \omega / C \qquad \cdots(4)$$

$$Eqn.(3) \Rightarrow f(x, z = Z) = E_o e^{-i2\pi\sqrt{\alpha^2 - K^2}\varepsilon} \int_{-\frac{\omega}{2\pi C}}^{\frac{\omega}{2\pi C}} d\alpha_x e^{-i2\pi\alpha_x x} e^{-i2\pi\sqrt{\alpha^2 - \alpha_x^2}(Z-\varepsilon)} \frac{\sin(\alpha_x - K)w}{\alpha_x - K} \quad \cdots(5)$$

Notes: Eqn. (4) fulfills all our notions about far-field microscope and its inability to carry information beyond certain spatial frequency

Eqn. (5) integral doesn't vanish for $K > \omega / C$, such that high-frequency elements still contribute to the signal arriving at z=Z (far field).

Eqn. (4) collapses to (5) when w (aperture width) is large, i.e. $\frac{\sin(\alpha_x - K)w}{\alpha_x - K} \rightarrow\rightarrow \delta(\alpha_x - K)$

In the near-field, evanescent terms must be taken into account, due to the convolution of the tip and the sample.

Quantum confinement

Quantum-confined materials refer to structures which are constrained to nanoscale lengths in one, two or all three dimensions. The length along which there is Quantum confinement must be small than de Broglie wavelength of electrons for thermal energies in the medium.

Thermal Energy, $E = \frac{mv^2}{2} = kT$ **de Broglie Wavelength,** $\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2mkT}}$

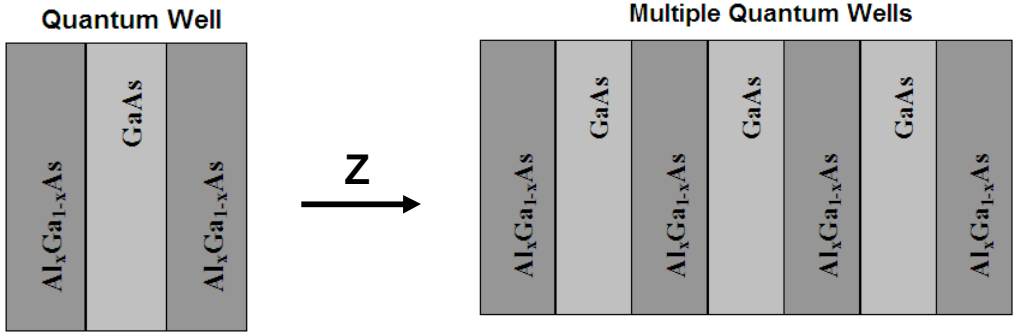
Material	Electron effective mass	Hole effective mass
Group IV		
Si (4.2K)	1.08 m_e	0.56 m_e
Ge	0.55 m_e	0.37 m_e
III-V		
GaAs	0.067 m_e	0.45 m_e
InSb	0.013 m_e	0.6 m_e
II-VI		
ZnO	0.19 m_e	1.21 m_e
ZnSe	0.17m_e	1.44 m_e

For T = 10 K, the calculated λ in GaAs is 162 nm for Electrons and 62 nm for Holes

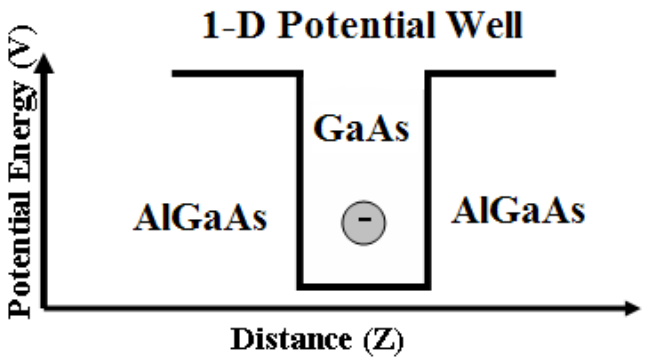
For effective Quantum-confinement, one or more dimensions must be less than 10 nm. Structures which are Quantum-confined show strong effect on their Optical Properties. Artificially created structures with Quantum-confinement on one, two or three dimensions are called, Quantum Wells, Quantum Wires and Quantum Dots respectively.

Quantum Confinement

Nanoscale Confinement in 1-Dimension results in a "Quantum Well"



At 300 K, The band gap of GaAs is 1.43 eV while it is 1.79 eV for AlxGa1-xAs (x=0.3). Thus the electrons and holes in GaAs are confined in a 1-D potential well of length L in the Z-direction.



Quantization of energy into discrete levels has applications for fabrication of new solid-state lasers. Two or more Quantum wells side-by-side give rise to Multiple Quantum Wells (MQM) structure.

Motion is confined only in the Z-direction. For electrons and holes moving in the Z-direction in low bandgap material, their motion can be described by Particle in a Box. If the depth of Potential Well is V, for energies E<V, we can write,

$$E_{n,k_x,k_y} = E_C + \frac{n^2h^2}{8m_e^*L^2} + \frac{h^2(k_x^{\,2} + k_y^{\,2})}{8\pi^2 m_e^*}$$

n = 1, 2, 3,.....

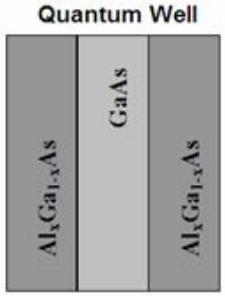
$p_x = (h/2\pi)k_x$ and $p_y = (h/2\pi)k_y$ can take continuous value and m_e^* is the effective mass of electron

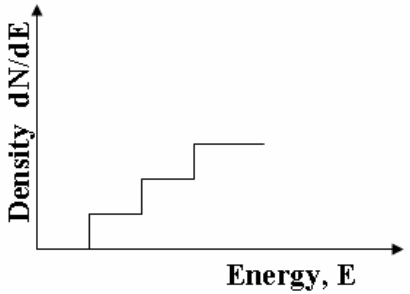
Quantum Confinement

Quantum Well: 1D Confinement

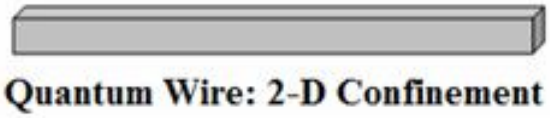
Due to 1-D confinement, the number of continuous energy states in the 2-D phase space satisfy

$$2mE_{2D} = p_x^2 + p_y^2$$



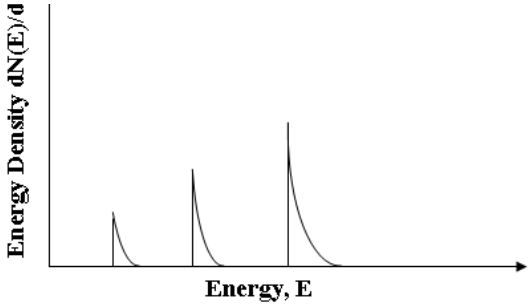


Quantum Wire: 2D Confinement



2D confinement in X and Z directions. For wires (e.g. of InP, CdSe). with rectangular cross-section, we can write:

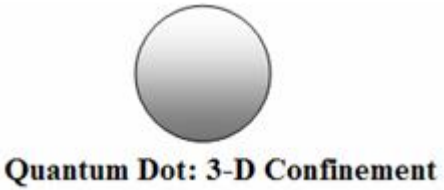
$$E_{n_1,n_2,k_y} = E_C + \frac{n_1^2 h^2}{8m_e^* L_x^2} + \frac{n_2^2 h^2}{8m_e^* L_z^2} + \frac{h^2 k_y^2}{8\pi^2 m_e^*}$$

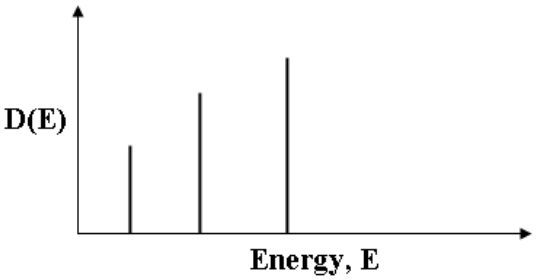


Quantum Dot: 3D Confinement

For a cubical box with the discrete energy levels are given by:

$$E_{n_1,n_2,n_3} = E_C + \frac{h^2}{8m_e^*}\left(\frac{n_1^2}{L_x^2} + \frac{n_2^2}{L_y^2} + \frac{n_3^2}{L_z^2}\right)$$

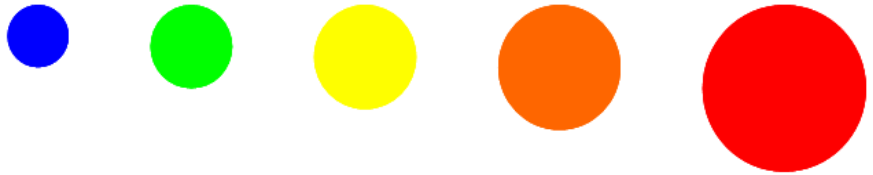




Quantum Confinement

Size Dependence of Optical Properties

In general, confinement produces a blue shift of the band-gap. Location of discrete energy levels depends on the size and nature of confinement.



Increase of Oscillator Strengths

This implies increase of optical transition probability. This happens anytime the energy levels are squeezed into a narrow range, resulting in an increase of energy density. The oscillator strengths increase as the confinement increases from Bulk to Quantum Well to Quantum Wire to Quantum Dot.

Computational Nanophotonics

- Analytical approach hampered by over-simplifying assumptions
  - Perfect conductivity, zero thickness materials, semi-infinite structures, ...
- Frequency vs. Time domain?
- Computational resources becoming less constraining
  - Very complex problems being tackled
- Finite Difference Time Domain (FDTD)
- Frequency Domain Integral-differential

Computational Nanophotonics

Time Domain

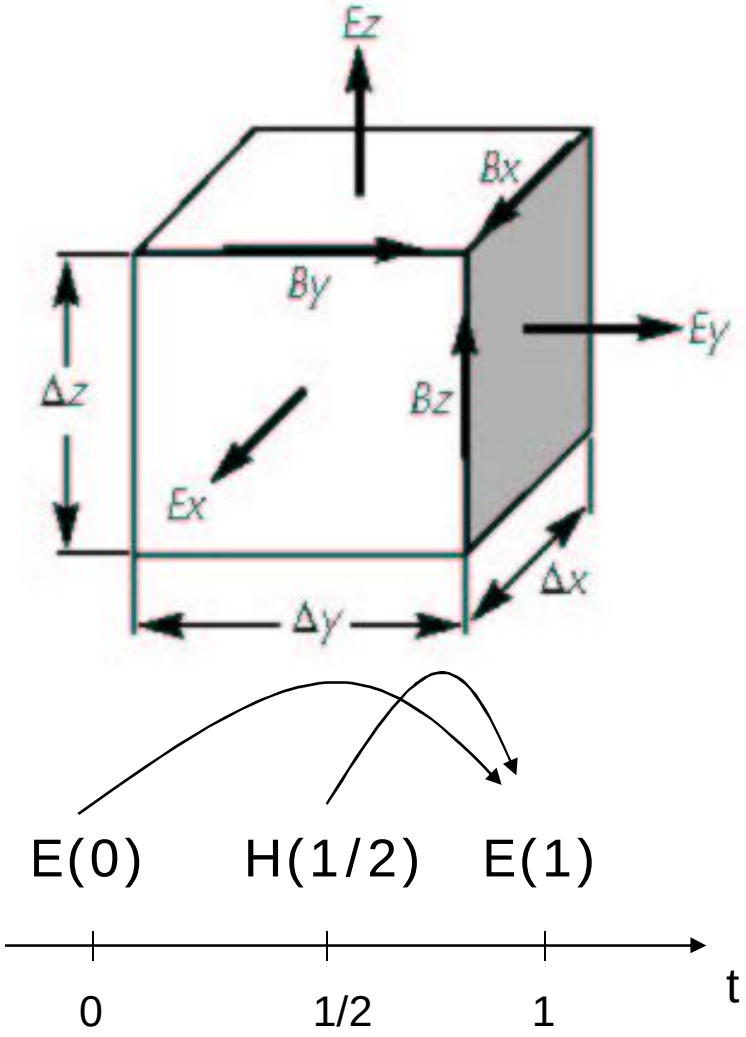
- Numerical integration of Ampere/Faraday
- Impulse excitation
- Numerical integration to get steady state
- Relate time series to frequency domain via F.T.
- Some problems with highly dispersive *media* (convolutional response)
- No big things to invert but lots of memory
- Sophisticated variable mesh

Frequency Domain

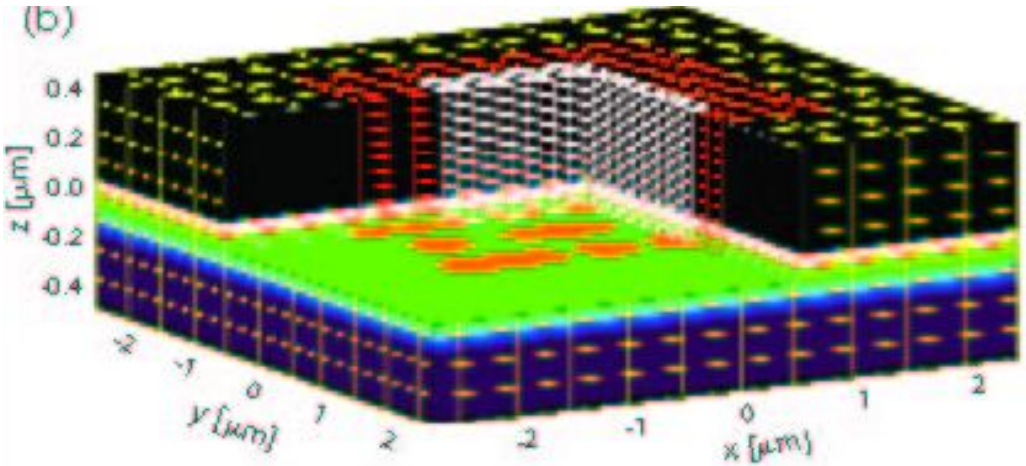
- Time harmonic excitation (steady state)
- Boundary value problem based on integro-differential equation
- Big things to invert (stability/accuracy issues possible)
- Relate to time domain by F.T.

Finite Difference Time Domain (FDTD)

Yee Cell – Space/Time

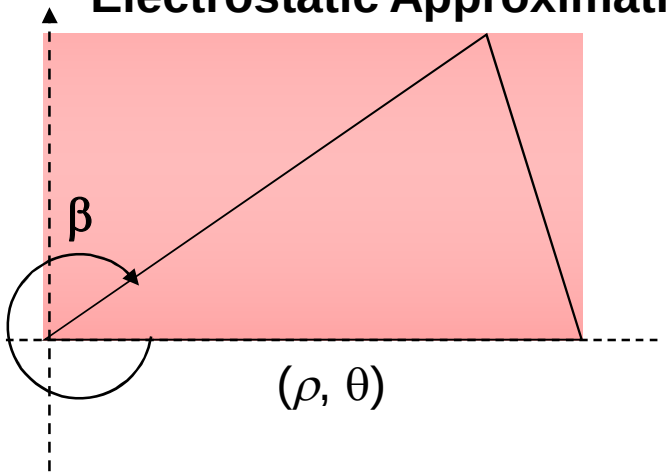


$$E_x(n+1,i,j,k) = E_x(n,i,j,k) + \frac{\Delta t}{\varepsilon(i,j,k)} \left\{ \frac{H_z(n+\tfrac{1}{2},i,j+\tfrac{1}{2},k) - H_z(n+\tfrac{1}{2},i,j-\tfrac{1}{2},k)}{\Delta y} - \frac{H_y(n+\tfrac{1}{2},i,j,k+\tfrac{1}{2}) - H_y(n+\tfrac{1}{2},i,j,k-\tfrac{1}{2})}{\Delta z} \right\}$$



Static State Computation

Electrostatic Approximation



Solve Laplace equation

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial\Phi}{\partial\rho}\right)+\frac{1}{\rho^2}\frac{\partial^2\Phi}{\partial\theta^2}=0$$

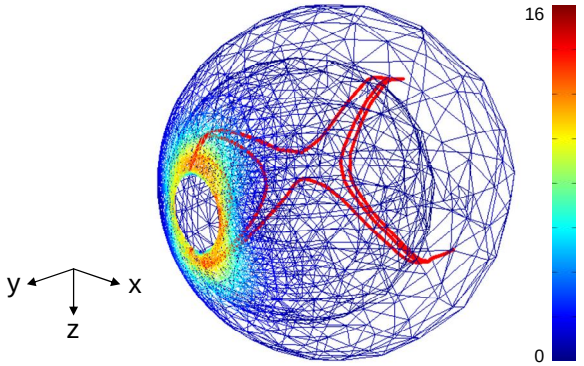
Charge density

$$\sigma(\rho)=\varepsilon E(\rho,0)=\frac{\varepsilon\pi a}{\beta}\rho^{(\pi/\beta)-1}$$

Singularity near the sharp tip

$$\beta>\pi \Rightarrow \sigma(\rho\to 0)\to\infty$$

Finite Element Simulation



Solve Harmonic Wave Equation

$$\nabla\times(\mu^{-1}\nabla\times E)-\omega^2\varepsilon E=0$$

$$\nabla\times(\varepsilon^{-1}\nabla\times H)-\omega^2\mu H=0$$

For Plane Wave

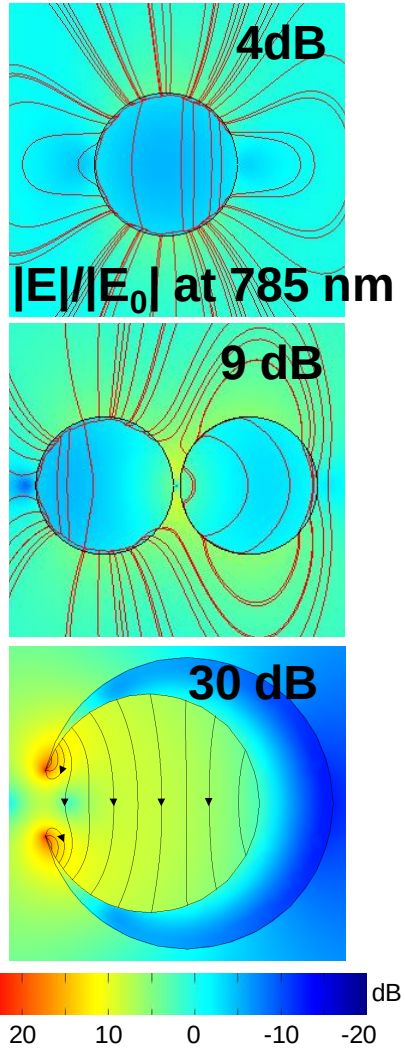
$$\nabla\cdot\nabla E_z-\varepsilon k_0{}^2E_z=0$$

$$-\nabla\cdot(\varepsilon\nabla H_z)-k_0{}^2H_z=0$$

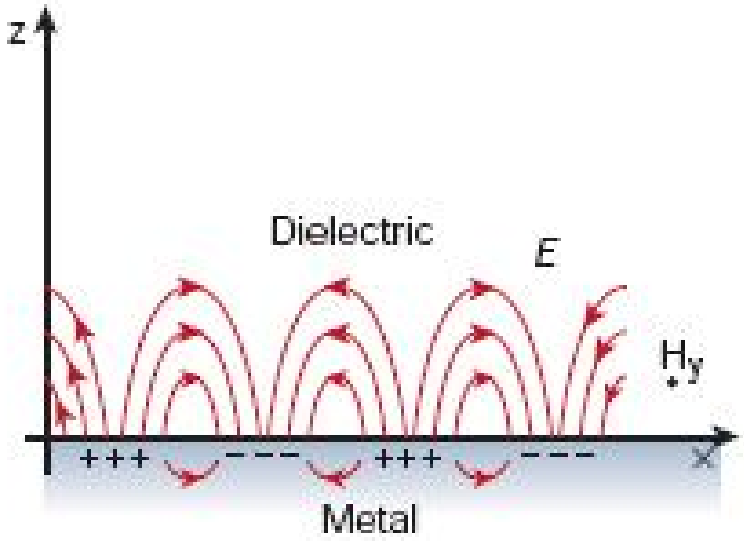
Low-reflecting Boundary Condition

$$n\times\sqrt{\mu}H+\sqrt{\varepsilon}E_z=2\sqrt{\varepsilon}E_{0z}$$

$$n\times\sqrt{\varepsilon}E-\sqrt{\mu}H_z=-2\sqrt{\mu}H_{0z}$$



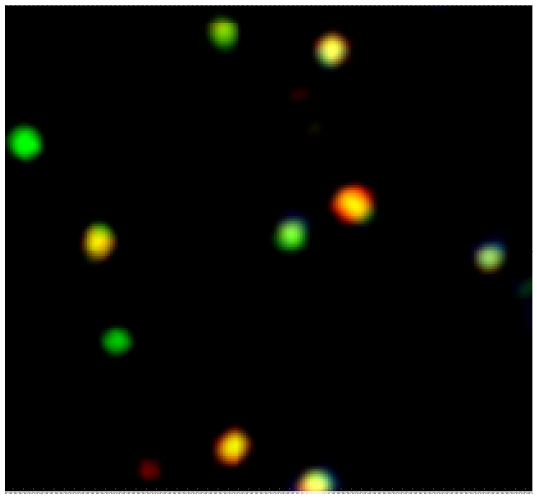
Plasmonics

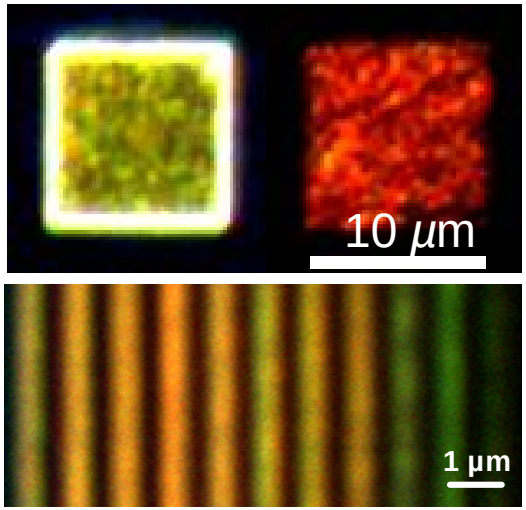


Transverse EM wave coupled to a plasmon (wave of charges on a metal/dielectric interface) = SPP (surface plasmon polariton)

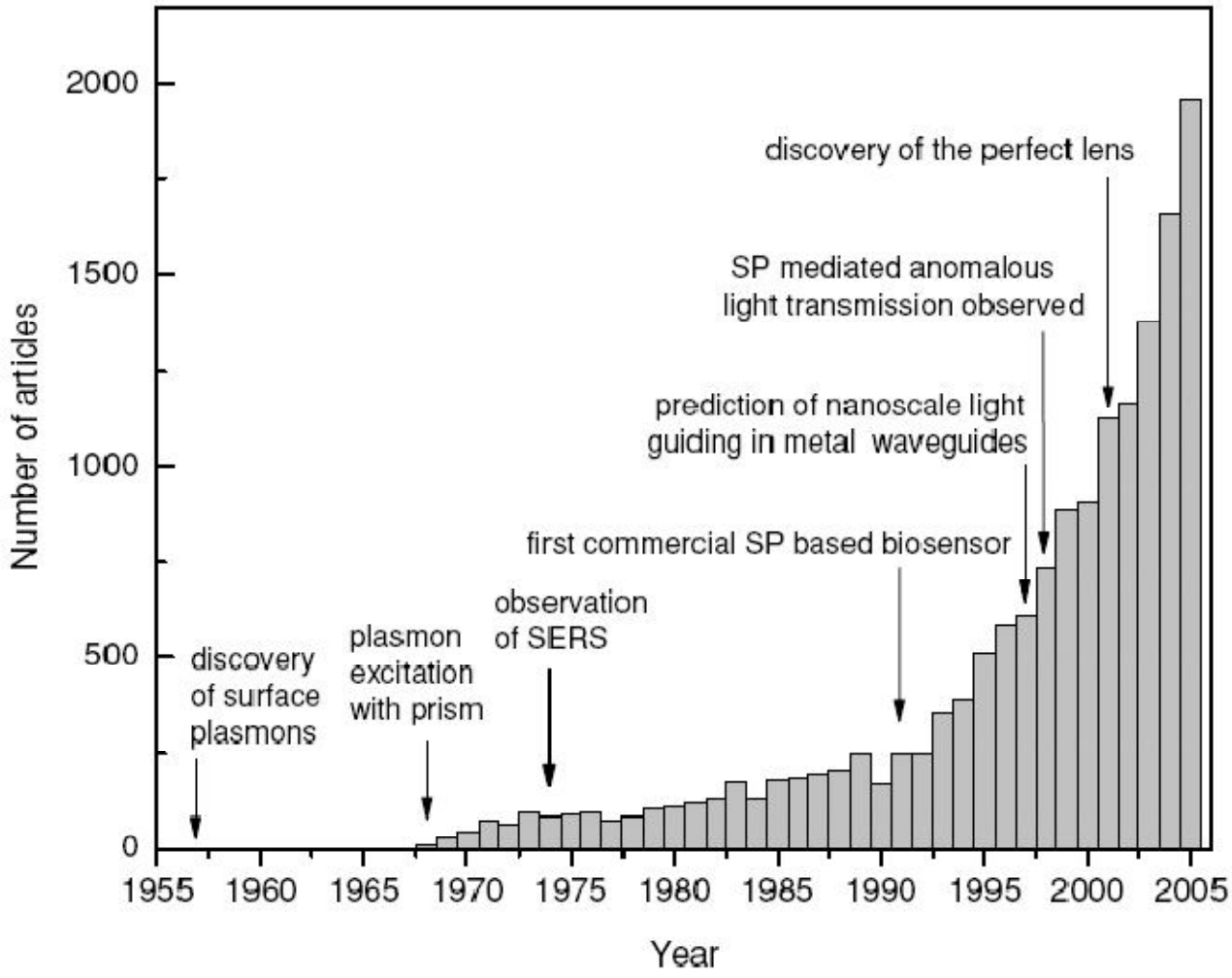
Note: the wave has to have the component of E transverse to the surface (be TM-polarized).

Polariton – any coupled oscillation of photons and dipoles in a medium



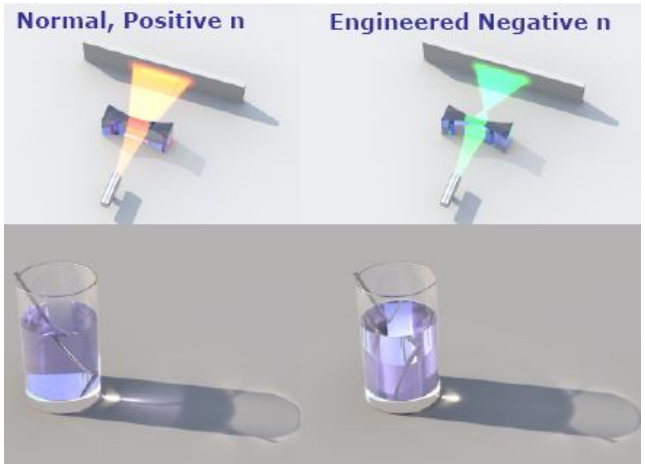


Plasmonics Research

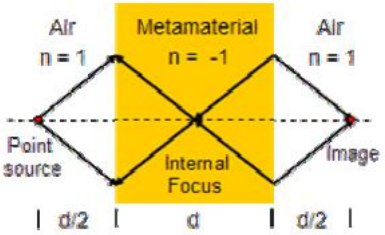


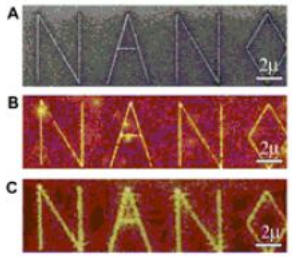
Details in Prof. Nick Fang's Lecture

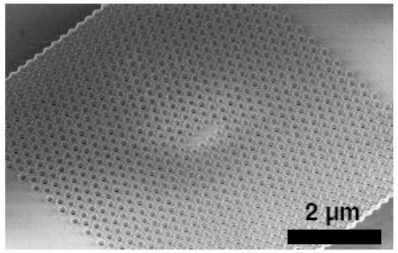
Metamaterials

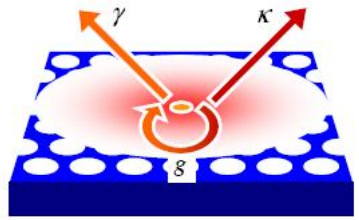


Hormann et al, Optics Express (2007)

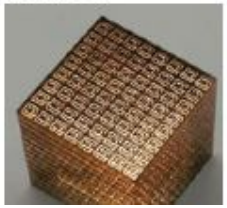


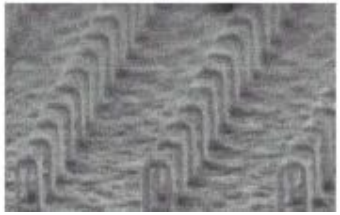






- Engineered material responses, electrical permittivity ε(ω) and magnetic permeability μ(ω).
  - Fields of individual nanostructures,
  - subwavelength scale, "effective medium limit"
  - resonant response to electric or magnetic field
- Possible to design metamaterials with a magnetic response at optical frequencies that no known natural material exhibits
- "Negative" Refractive index $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$
- Applications: Detection, Switching, Modulation of light, Engineered birefringence.

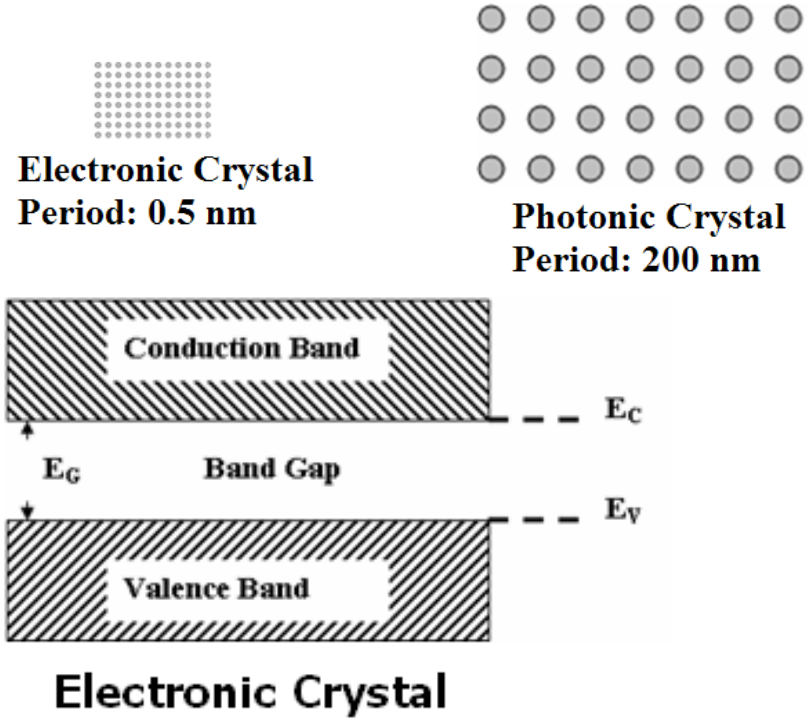




Details in Prof. Nick Fang's Lecture

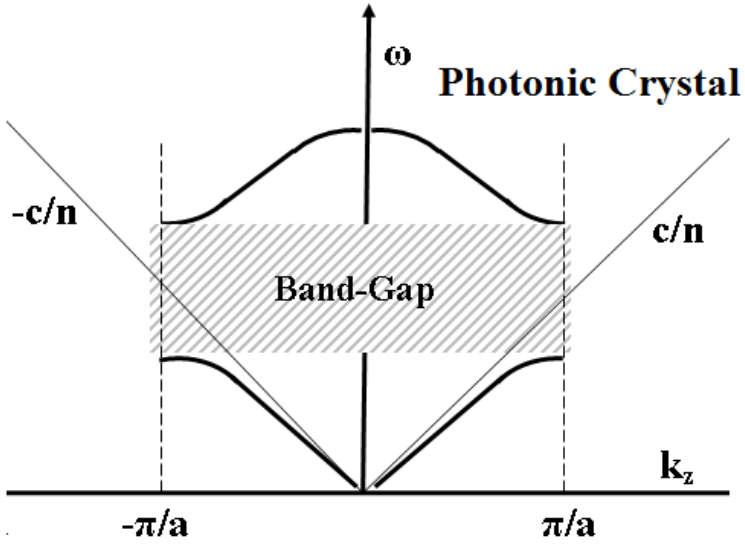
Photonic Crystal

The most striking similarity is the Band-Gap within the spectra of Electron and Photon Energies



Electronic Crystal

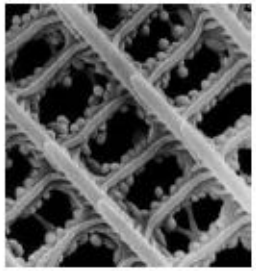
Solution of Schroedinger's equation in a 3D periodic coulomb potential for electron crystal forbids propagation of free electrons with energies within the Energy Band-Gap.



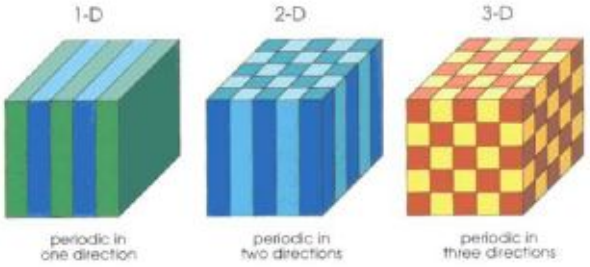
Likewise, diffraction of light within a Photonic Crystal is forbidden for a range of frequencies which gives the concept of Photonic Band-Gap. The forbidden range of frequencies depends on the direction of light with respect to the photonic crystal lattice. However, for a sufficiently refractive-index contrast (ratio n1/n2), there exists a Band-Gap which is omni-directional.

Photonic Crystal

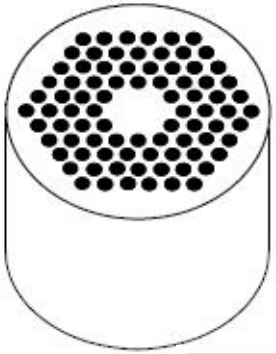
NATURAL

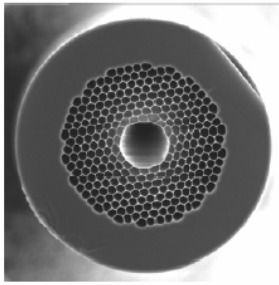


1D Photonic Crystal
(Bragg grating and thin film stack)

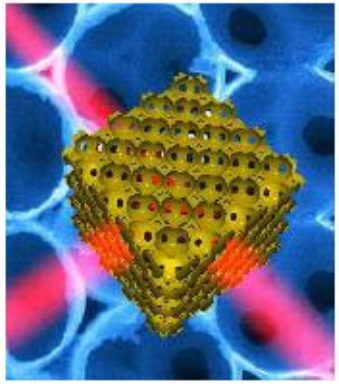


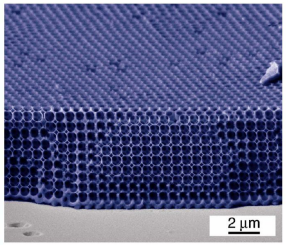
2D Photonic Crystal
MICROSTRUCTURED
OPTICAL FIBER





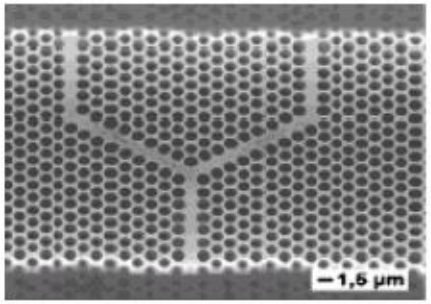
3D
PHOTONIC
CRYSTAL





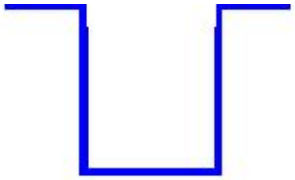
NECI 3D silicon PBG crystal - Y. Vlasov and D. Norris, NECI

2D Photonic Crystal
PLANAR WAVEGUIDE



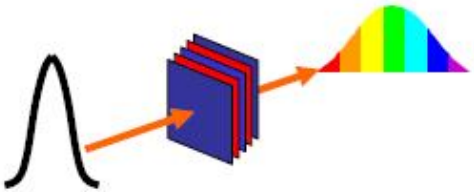
Photonic Crystal

ENHANCED NONLINEARITY

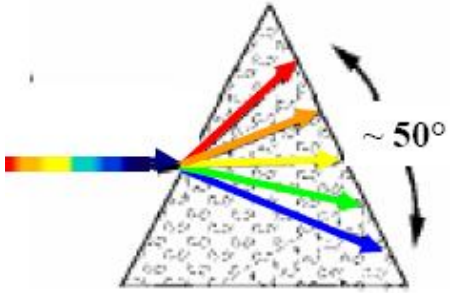


FILTER

HIGHLY DISPERSIVE ELEMENT

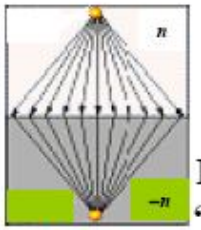


PHOTONIC CRYSTAL



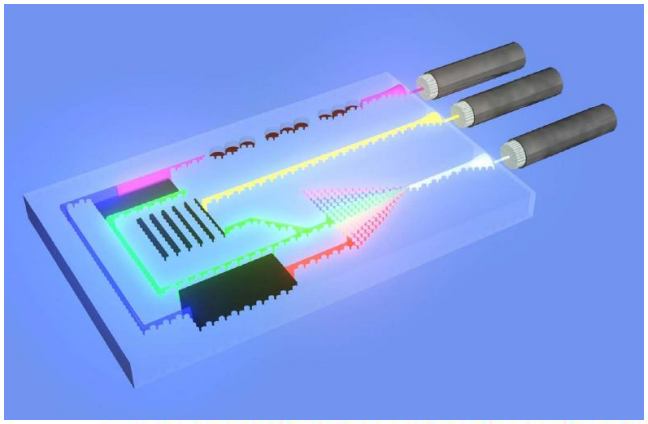
"SUPERPRISM"

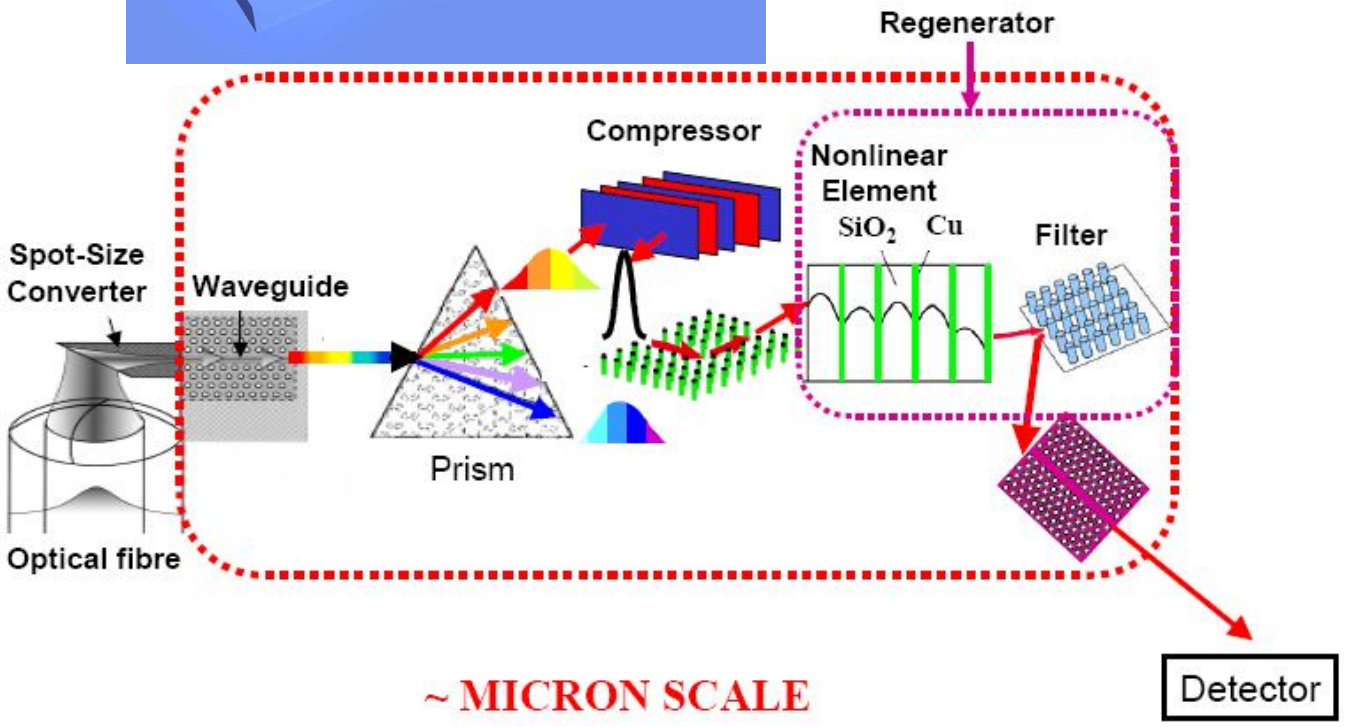
GUIDING AROUND SHARP CORNERS



NEGATIVE REFRACTION "SUPERLENS"

All-Optical Processor





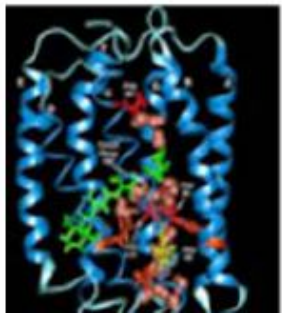
Molecular Nanophotonics

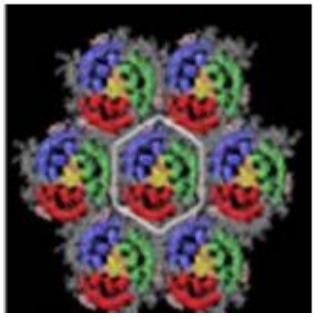
- **Bridge between current photonic systems and future approaches bringing in, eg:**
  - Access to further integration
  - Lower noise
- **Moving towards molecular photonics as the probable limit of integration which:**
  - will dissipate less energy
  - will occupy less volume
  - will require lower input signal
  - will probably rely on self-assembly
- **Molecules might compute, sense, act and serve as building block of more complex structures.**
  - Time scales
  - input- output schemes, algorithms, …

Molecular Nanophotonics

Bacterio-Rhodopsin (BR): natural second and third harmonic source

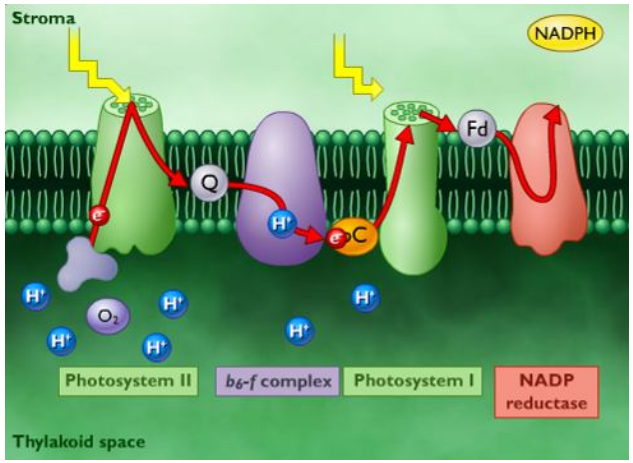
Bacteriorhodopsin has a hexagonal arrangement in the purple membrane fragments and behaves as a natural photonic crystal. The helical structure embeds a retinal chromophore.



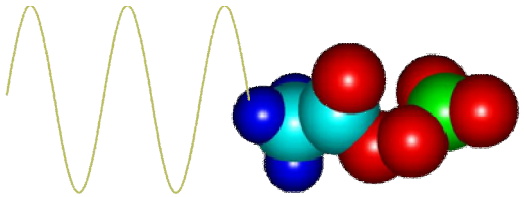


Photosynthetic Solar Cell

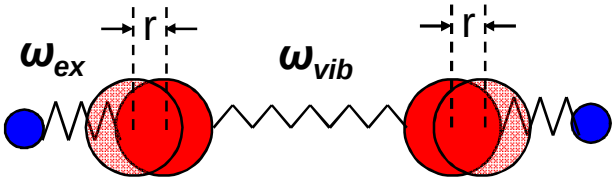
Molecular Nano Antenna

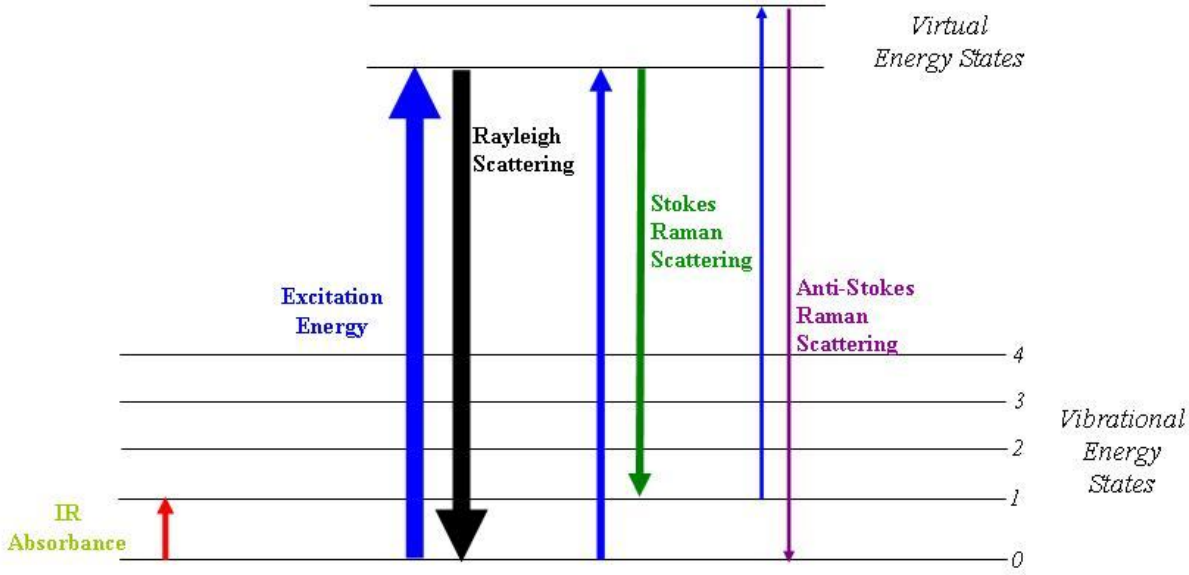


Molecular Nanophotonics



Coupled Spring Model





Excitation electric field

$$E = E_0 \cos(\omega_{ex} t)$$

Nuclear displacement

$$r = r_0 \cos(\omega_{vib} t)$$

Polarizonbility

$$\alpha = \alpha_0 + \left(\frac{\partial \alpha}{\partial r}\right)_0 r + \cdots$$

Dipole moment

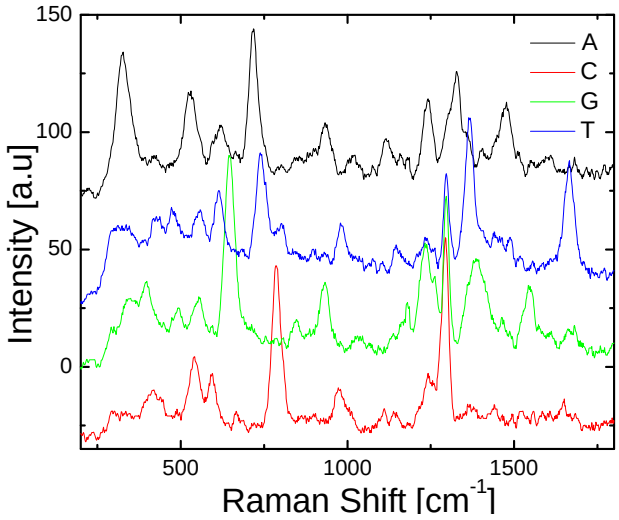
$$\mu = \alpha E = \alpha_0 E_0 \cos(\omega_{ex} t) + \left(\frac{\partial \alpha}{\partial r}\right)_0 r_0 E_0 \cos(\omega_{ex} t)\cos(\omega_{vib} t)$$

$$= \alpha_0 E_0 \cos(\omega_{ex} t) + \frac{1}{2}\left(\frac{\partial \alpha}{\partial r}\right)_0 r_0 E_0 \left[\cos\{(\omega_{ex} + \omega_{vib})t\} + \cos\{(\omega_{ex} - \omega_{vib})t\}\right]$$

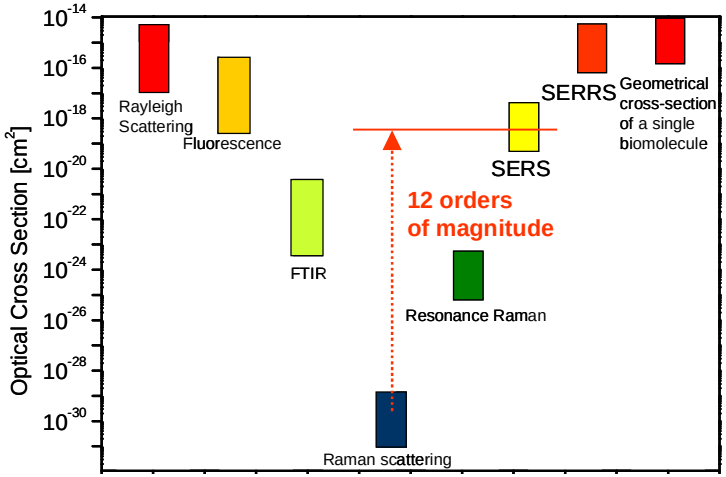
Rayleigh Scattering — Anti-Stokes line — Stokes line

Nanophotonic Interaction

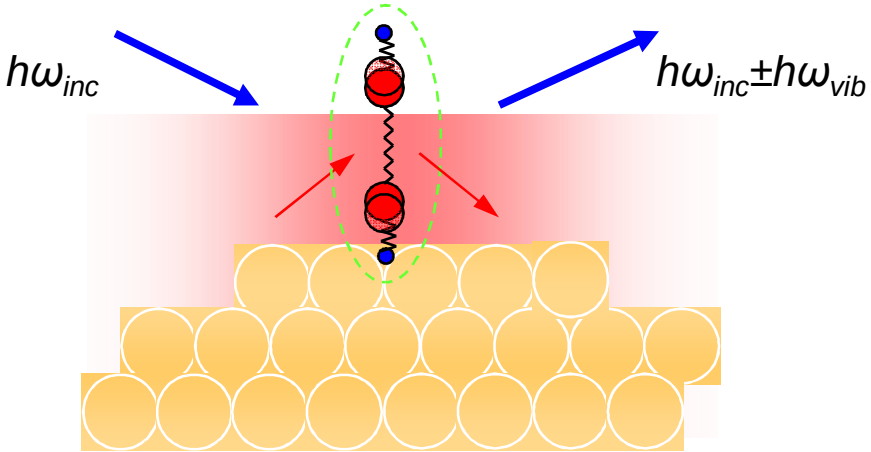
Raman Spectra of DNA Bases



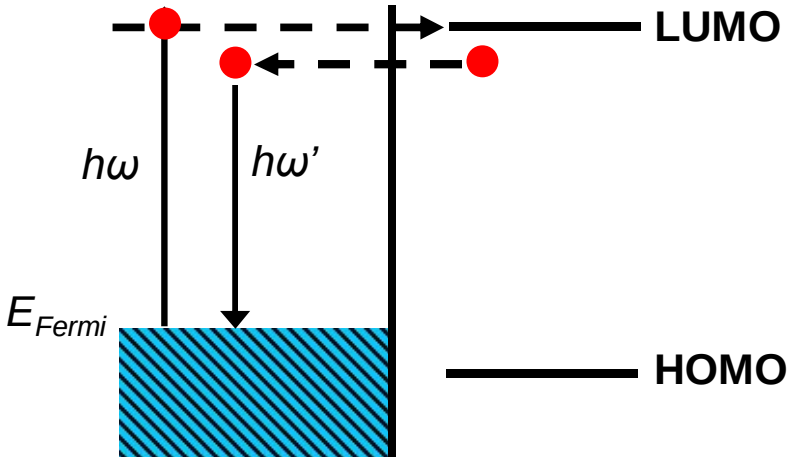
Optical Cross Section



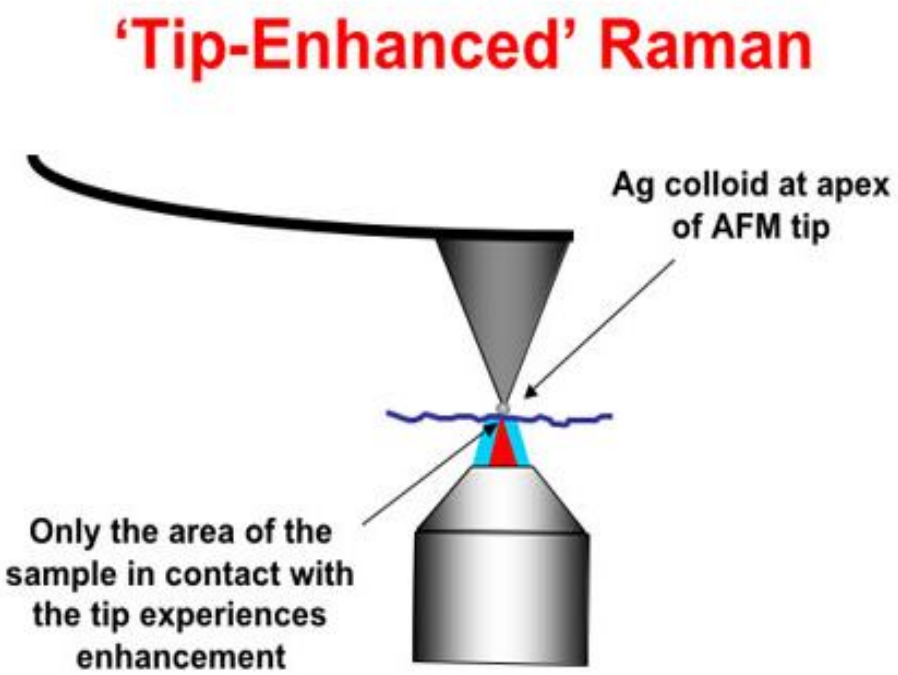
Electromagnetic Enhancement

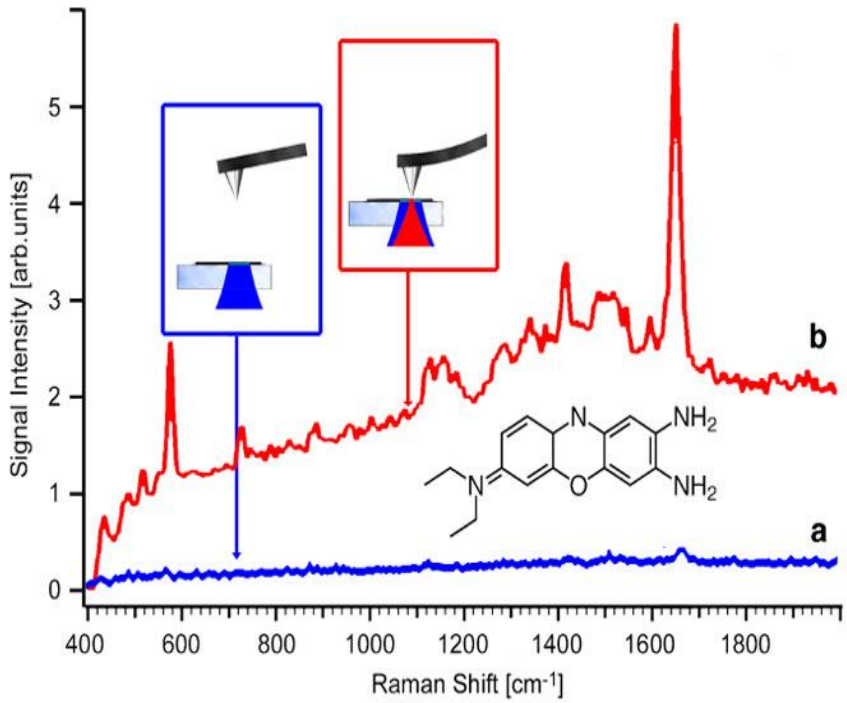


Chemical Enhancement



Nanophotonic Field Enhancement

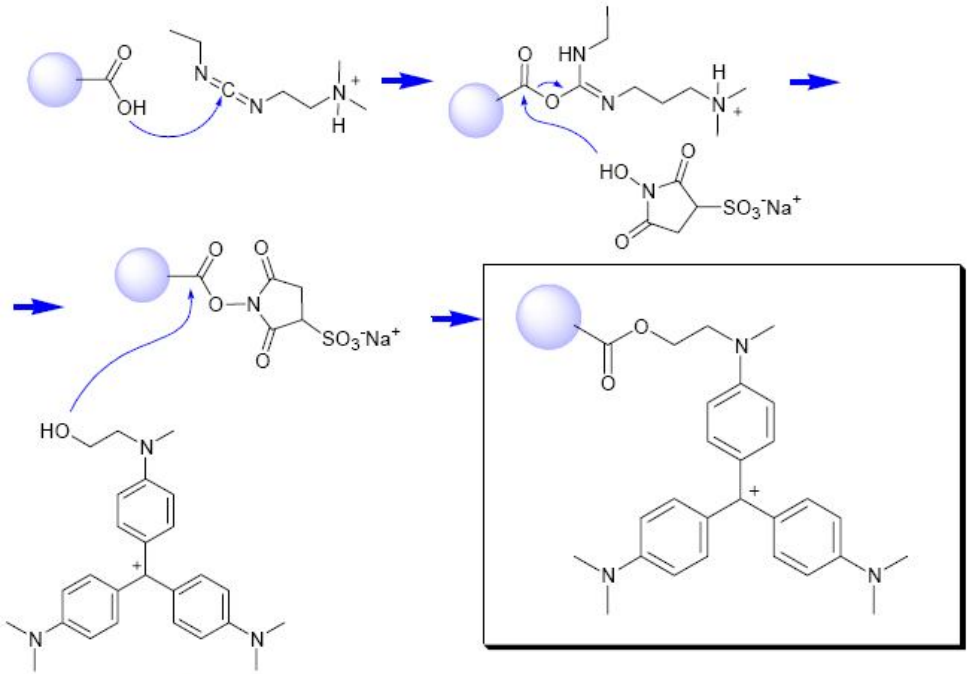


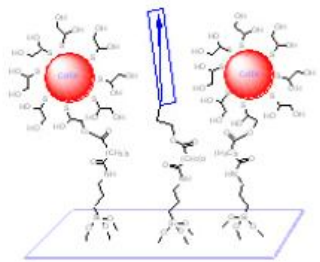


Cresyl blue SERS spectra. Adapted from Stöckle et al., *Chem. Phys. Lett.* **2000**, *318,* 131.

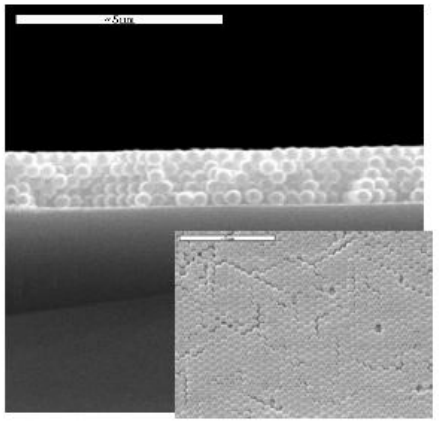
Hybrid Nanophotonics

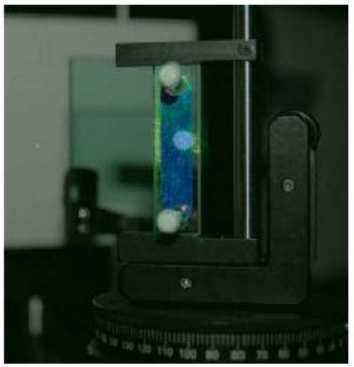
- Inorganic-organic hybrid structures





Coupling of QDs and NL chromophores is in progress

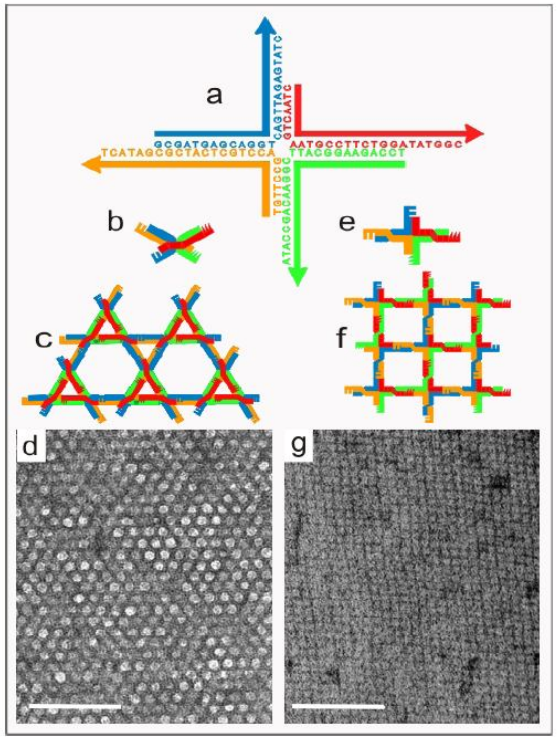




Green spot of the SHG light is clearly observed

Fabrication of Nanophotonics

- Advanced fabrication techniques available with nanometer precision
  - Bottom-up (Chemistry)
  - Top Down (Etching, ion-milling, etc)
  - Multiple dimensions, large scale, many materials



Achieved: self-assembled structures made by binding proteins onto nodes of self assembled DNA scaffold.

Now being pursued to make ordered arrays of metallic nano-particles and ordered arrays of fluorophores.

DNA can be fabricated with predetermined sequence so offering a programmable templating tool.

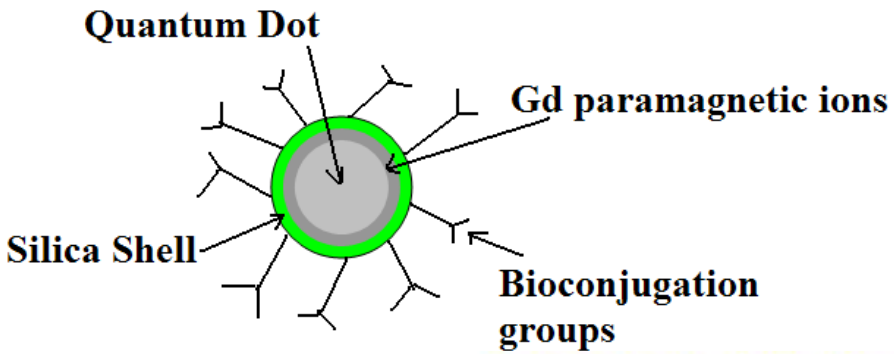
The technique offers atomic resolution.

Scale bars in micrographs: 100 nm.

U Oxford

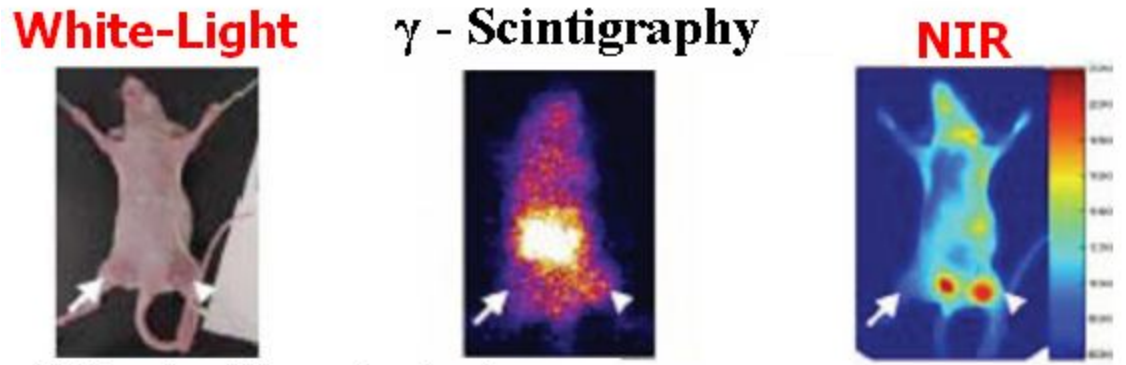
Nanophotonic Bioimaging

Nanoparticles are also used for bioimaging by non-optical techniques like Magnetic Resonance Imaging (MRI), Radioactive Nanoparticles as tracers to detect drug pathways or imaging by Positron Emission Tomography (PET), and Ultrasonic Imaging. For MRI, the magnetic nanoparticles could be made of



oxide particles which are coated with some biocompatible polymer.
Newer Nanoparticle Heterostructures have been investigated which offer the possibility of imaging by several techniques simultaneously. An example is Magnetic Quantum Dot.

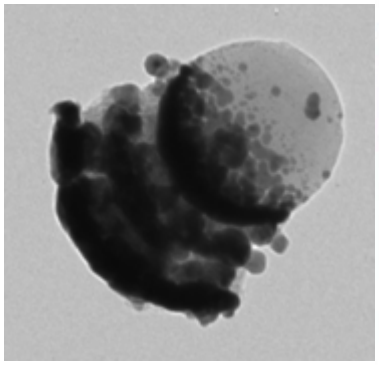
Imaging with Dual-Labeled Probes



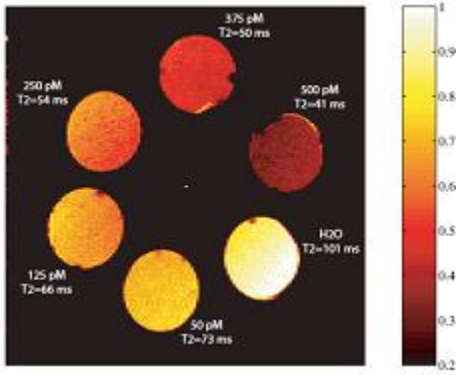
Multifunctional Nanoprobes-Louie: EAD289-Topics in Biophotonics, UC Davis

Nanophotonic Bioimaging

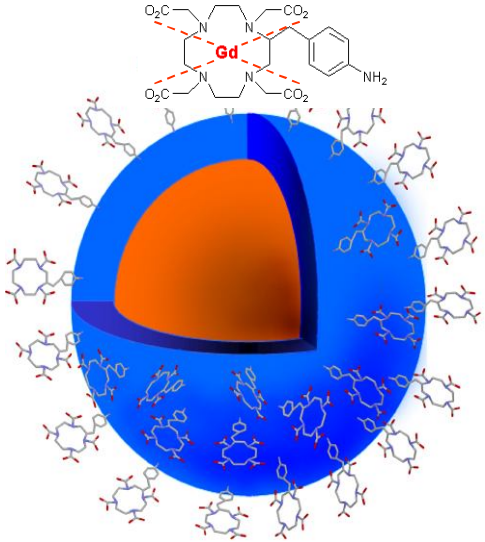
Dual-Functional Nanoprobes for Dual-Modality Animal Imaging



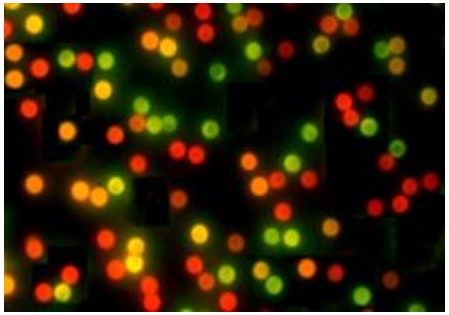
Photoacoustic

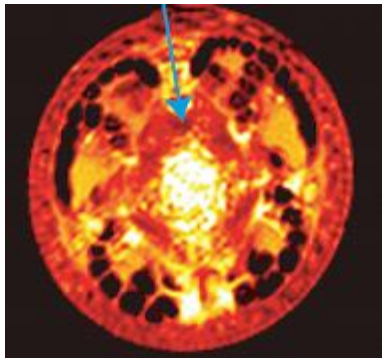


T2 MRI

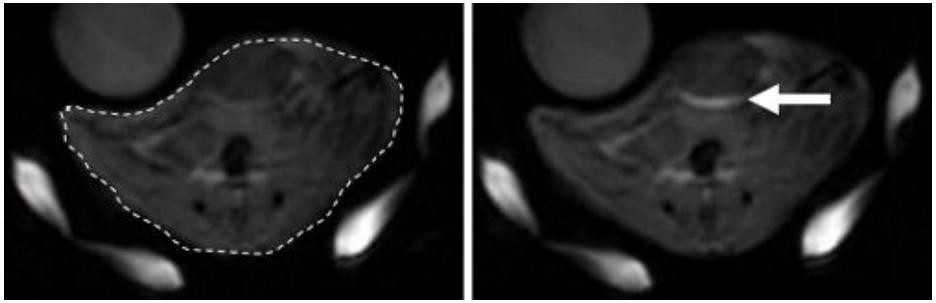


Fluorescence



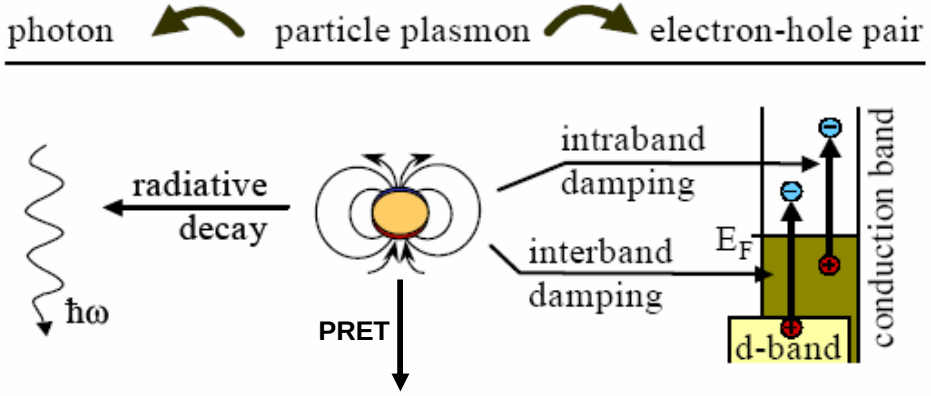


T1 MRI

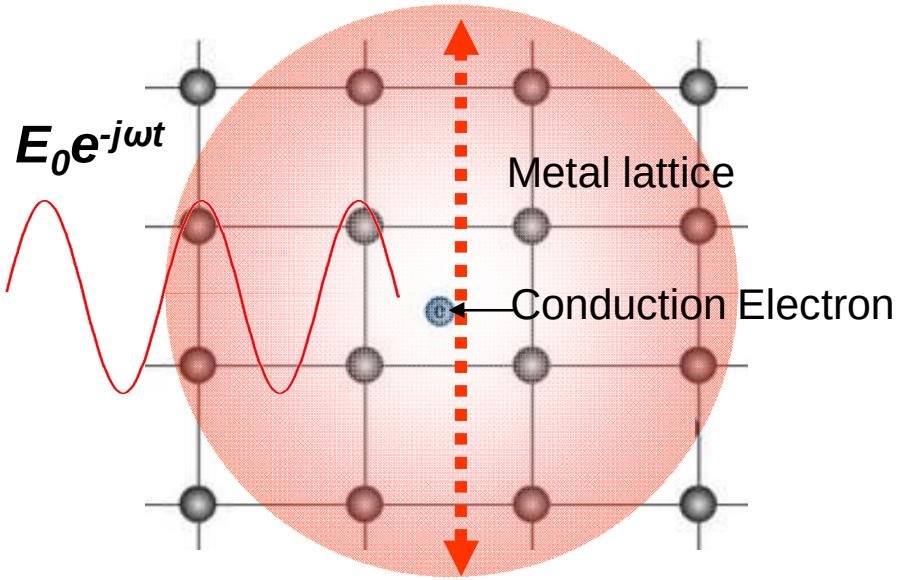


Bouchard and Liu et al, PNAS 2009

Nanophotonic Energy Conversion



Electron-Lattice Collision
(Electron-Phonon Relaxation)



Joule Heat due to Plasmon Current

$$Q = \left\langle j_{plasmon}(t) \cdot E_{plasmon}(t) \right\rangle_t$$

$$= -\mathrm{Re}\left[i\omega \frac{\varepsilon_{NP} - 1}{8\pi} E_0^2 \left| \frac{3\varepsilon_{medium}}{2\varepsilon_{medium} + \varepsilon_{NP}} \right|^2 \right]$$

$$\approx \frac{\omega}{8\pi} E_0^2 \left| \frac{3\varepsilon_{medium}}{2\varepsilon_{medium} + \varepsilon_{NP}} \right|^2 \mathrm{Im}\, \varepsilon_{NP}$$

Temperature Increase due to Photothermal Conversion

At steady state

$$\Delta T = \frac{a_{NP}^2 Q}{3\kappa}$$

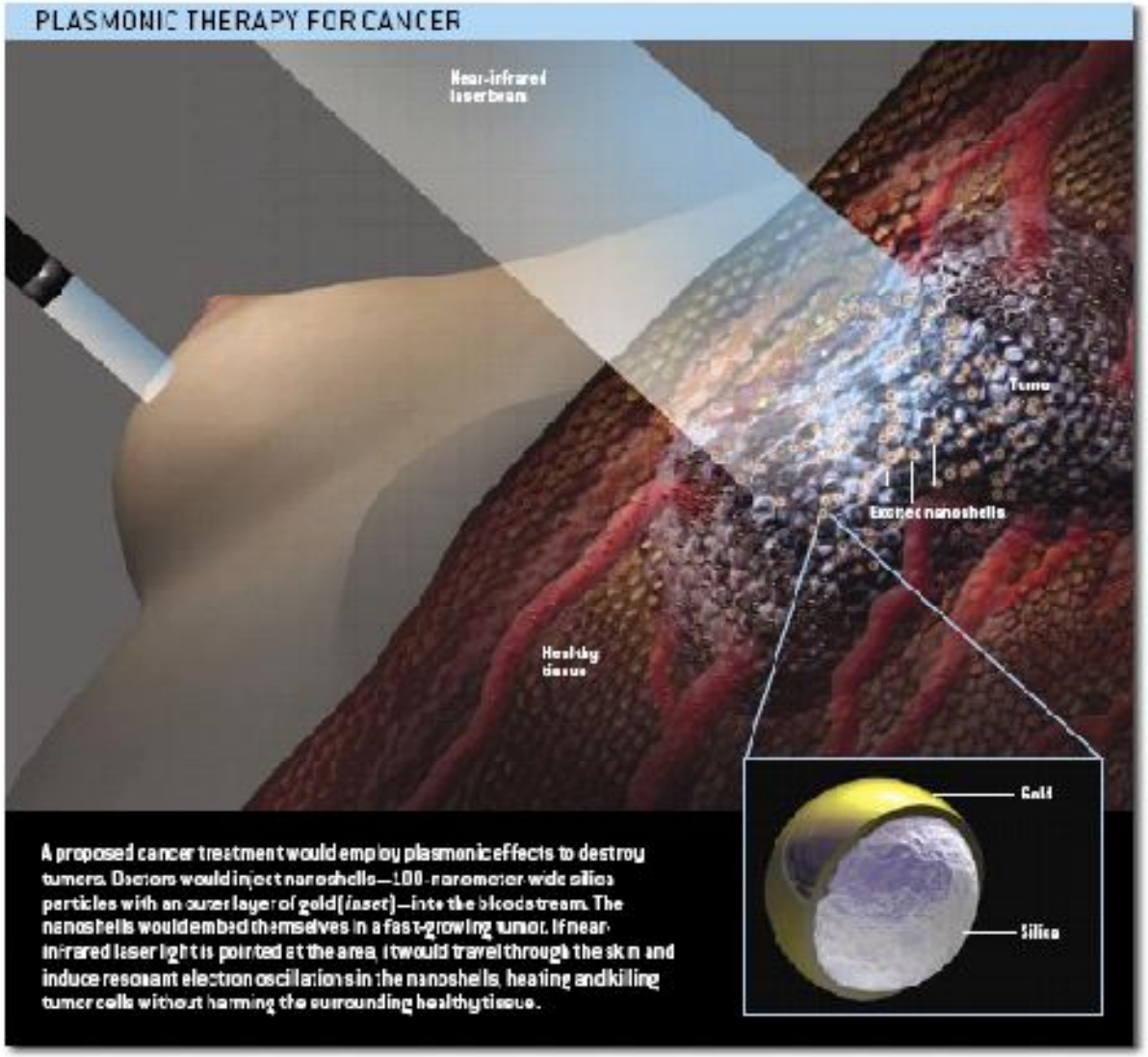
Light Intensity

$$I_0 = cE_0^2 \sqrt{\varepsilon_0} / 8\pi$$

$$\Rightarrow \Delta T = \frac{\omega I_0 a_{NP}^2}{3\kappa c\sqrt{\varepsilon_0}} \left| \frac{3\varepsilon_{medium}}{2\varepsilon_{medium} + \varepsilon_{NP}} \right|^2 \mathrm{Im}\, \varepsilon_{NP}$$

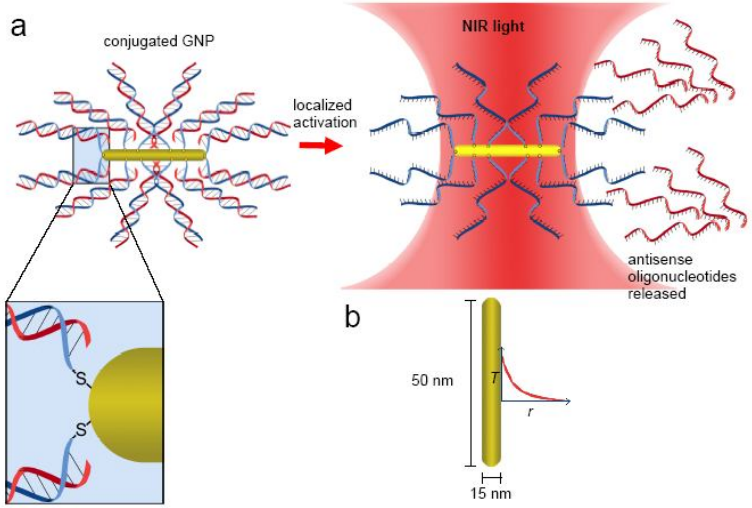
***NRL* 1**, 84-90 (2006)

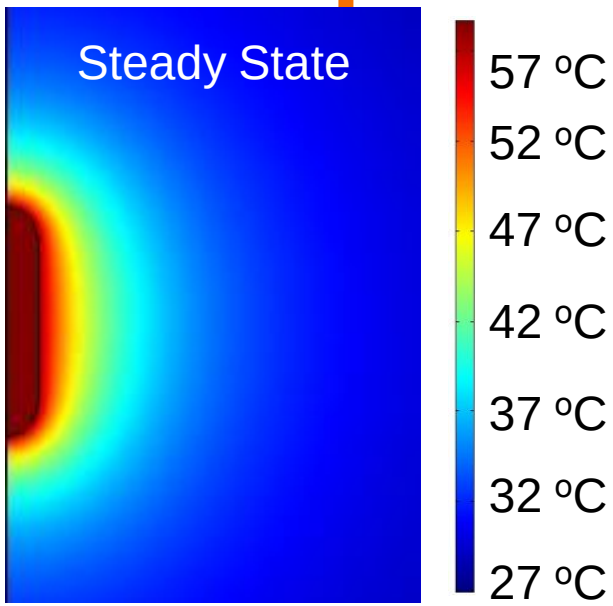
Nanophotonics Therapy

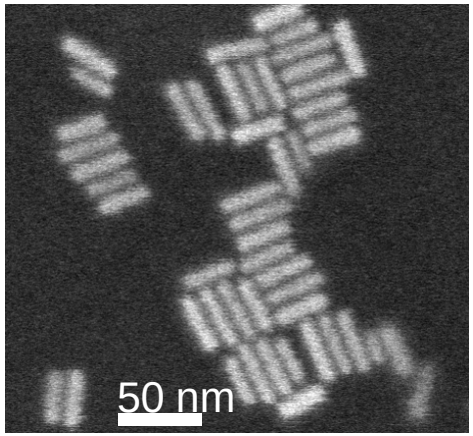


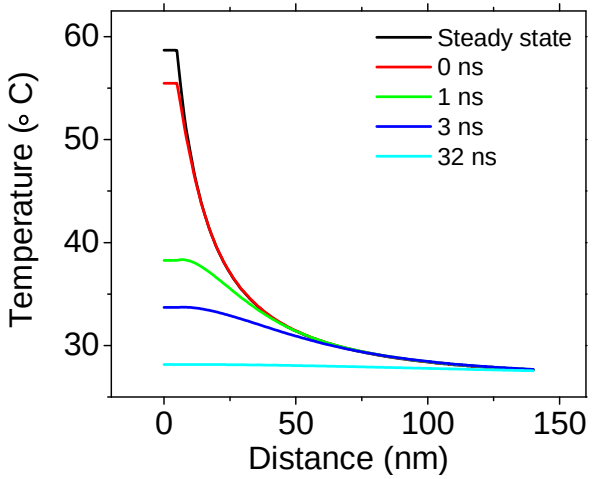
H. Atwater, Scientific American 2007

Nanophotonic Molecular Manipulation



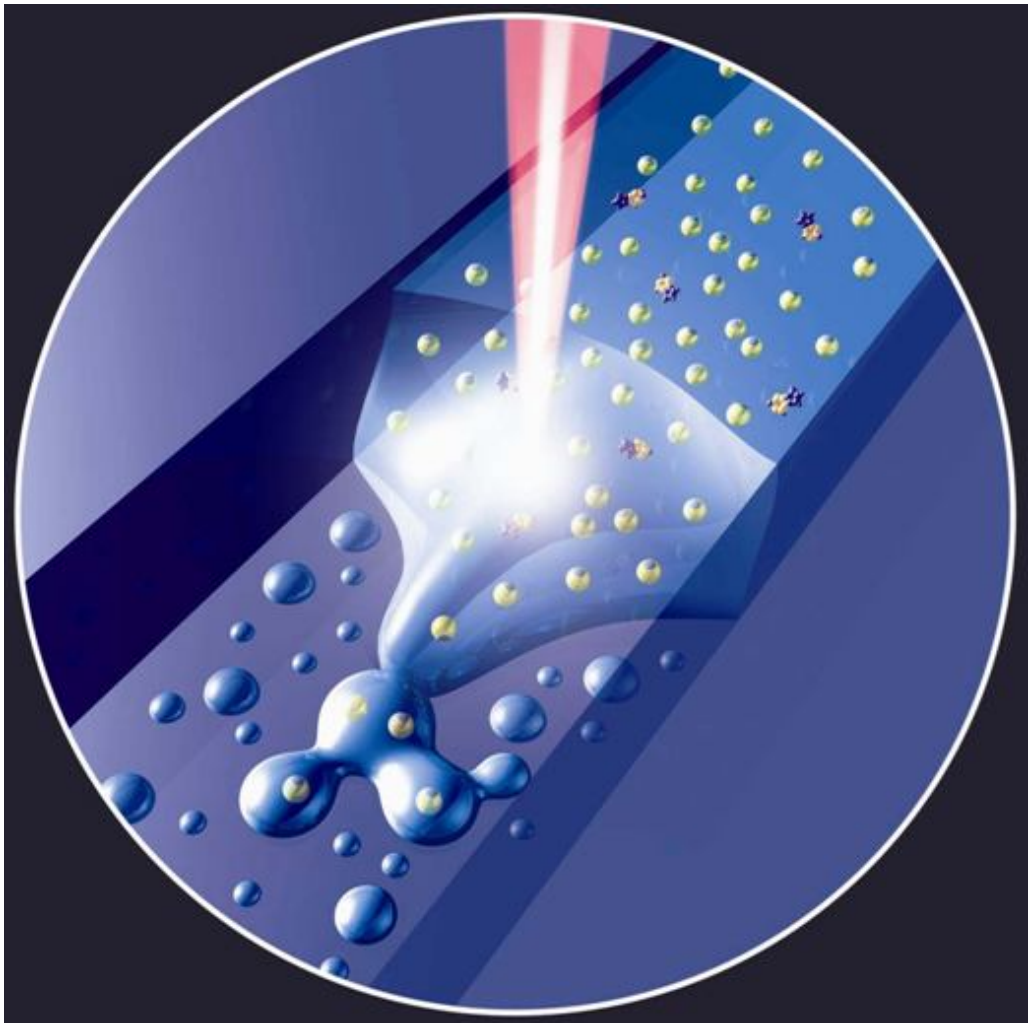


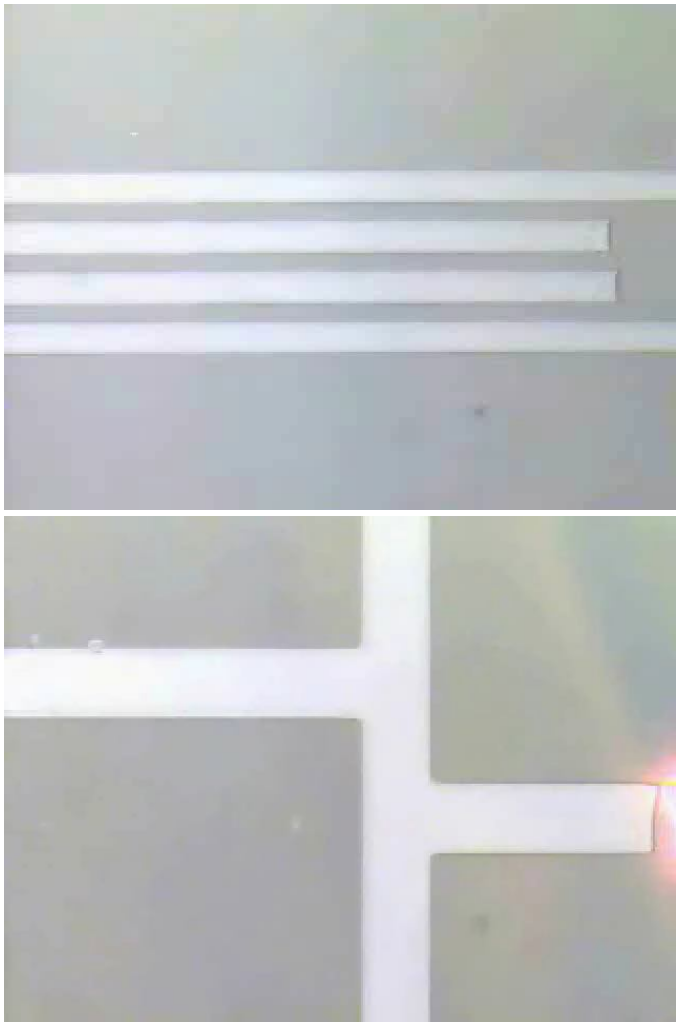




Lee et al, Nano Letter (2009)

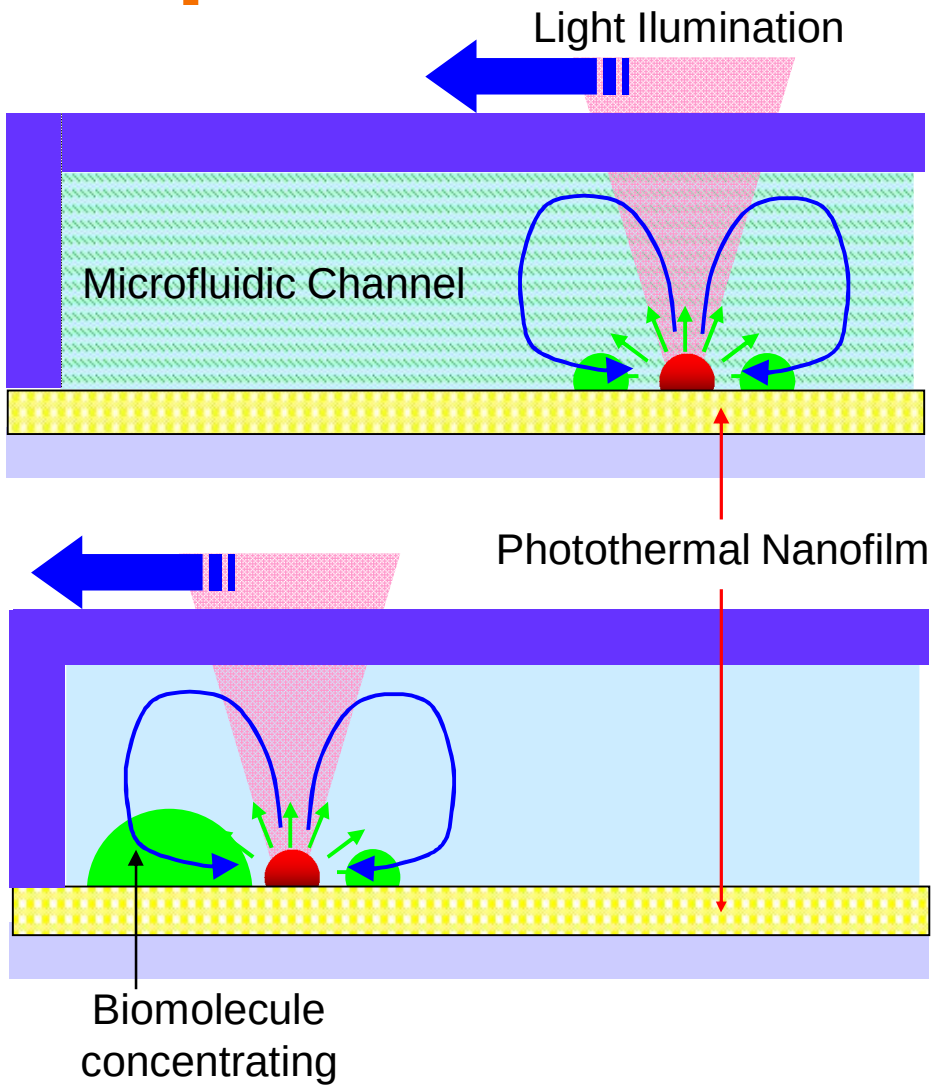
Nanophotonic Fluidic Manipulation

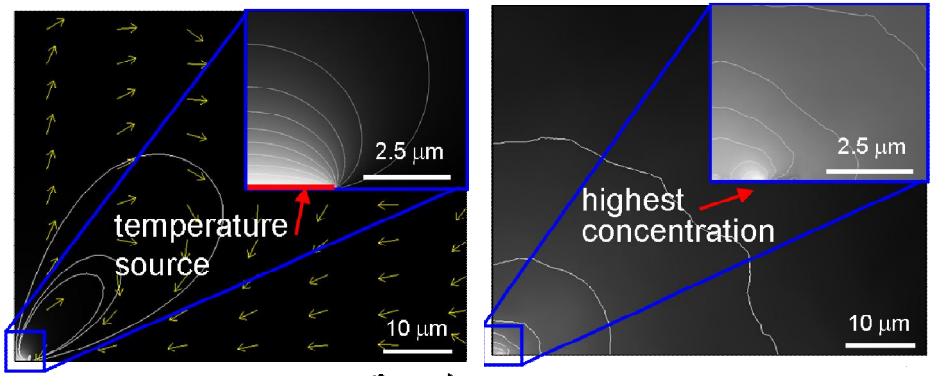




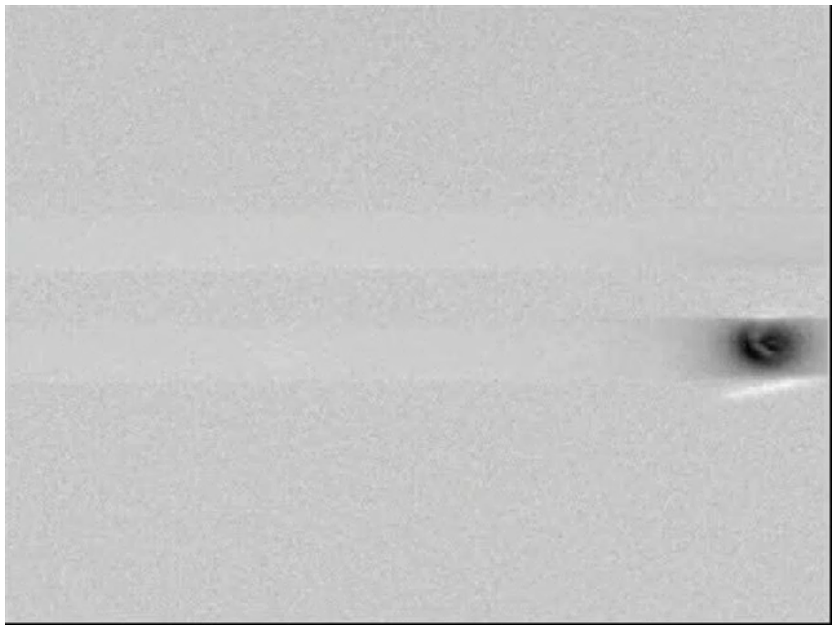
Liu *et al*, ***Nature Materials*** (2006)

Optofluidic Molecular Manipulation

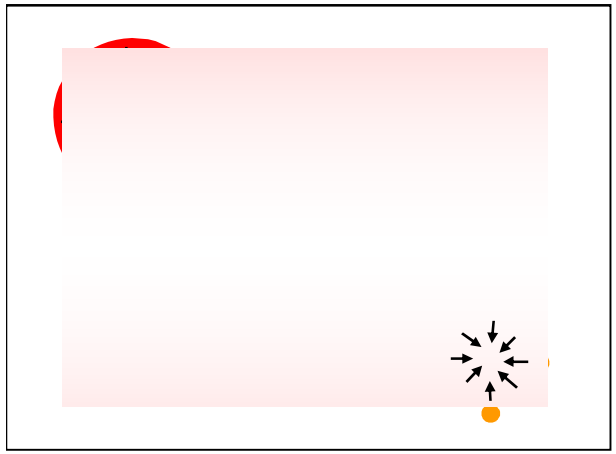




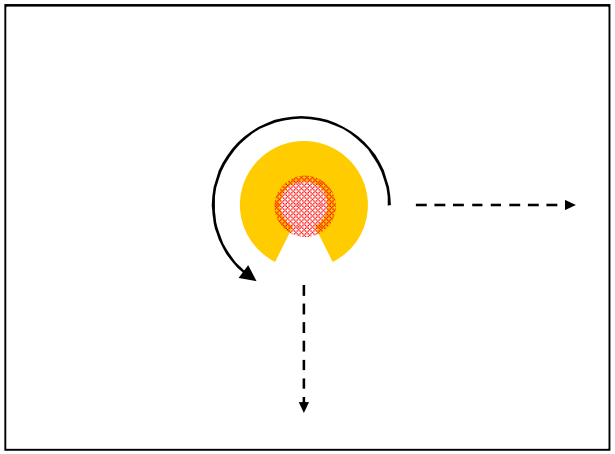
Optical Pre-Concentration of DNA



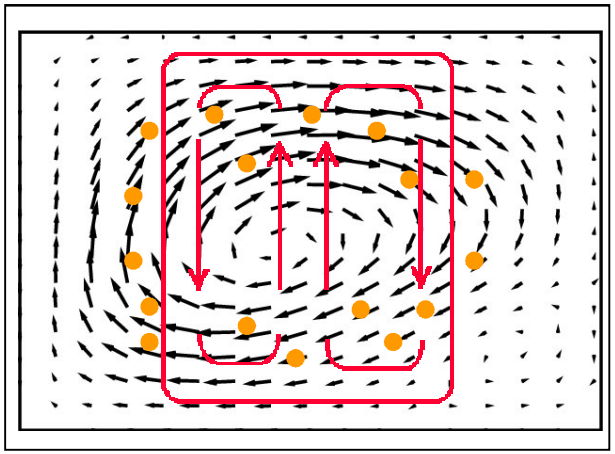
Nanophotonic Particle Manipulation



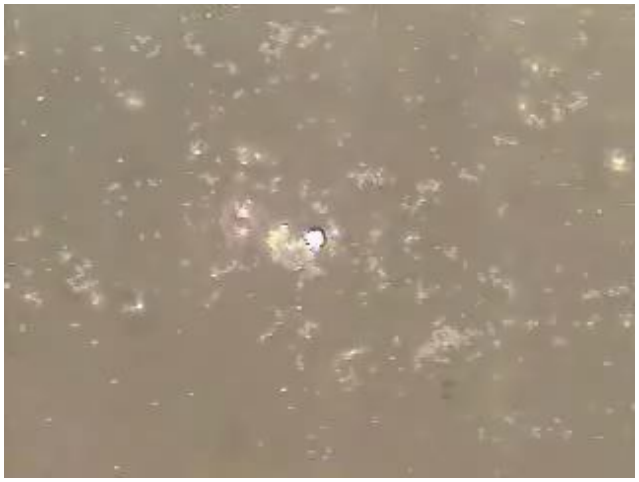
Conveyer



Rotor



Stirrer



Liu et al. Manuscript in preparation

Nanophotonics Market

	2004	2009	2014
Biomedical Markers (Chapter 3)	250	360	530
Chip Interconnects (Chapter 4)	0	0	20
Optocouplers (Chapter 4)	950	1,300	
Communication Lasers (Chapters 4 and 5)	151	281	473
Communication Passives (Chapter 5)	90	189	363
Specialty Fiber (Chapter 6)	2	5	11
Biochemical Fluidic Chips (Chapter 7)	1,000	1,690	2,790
Biomedical Tool Lasers (Chapter 7)	41	64	100
LEDs (Chapter 8)	198	1,100	
Solar Cells (Chapter 9)	126	388	
Displays (Chapter 10)	31,500	49,900	
Lithography Lasers (Chapter 11)	428	553	665

Nanophotonics:
Assessment of technology and Market Opportunities

By Strategies unlimited
Report OM-31, Jan. 2005

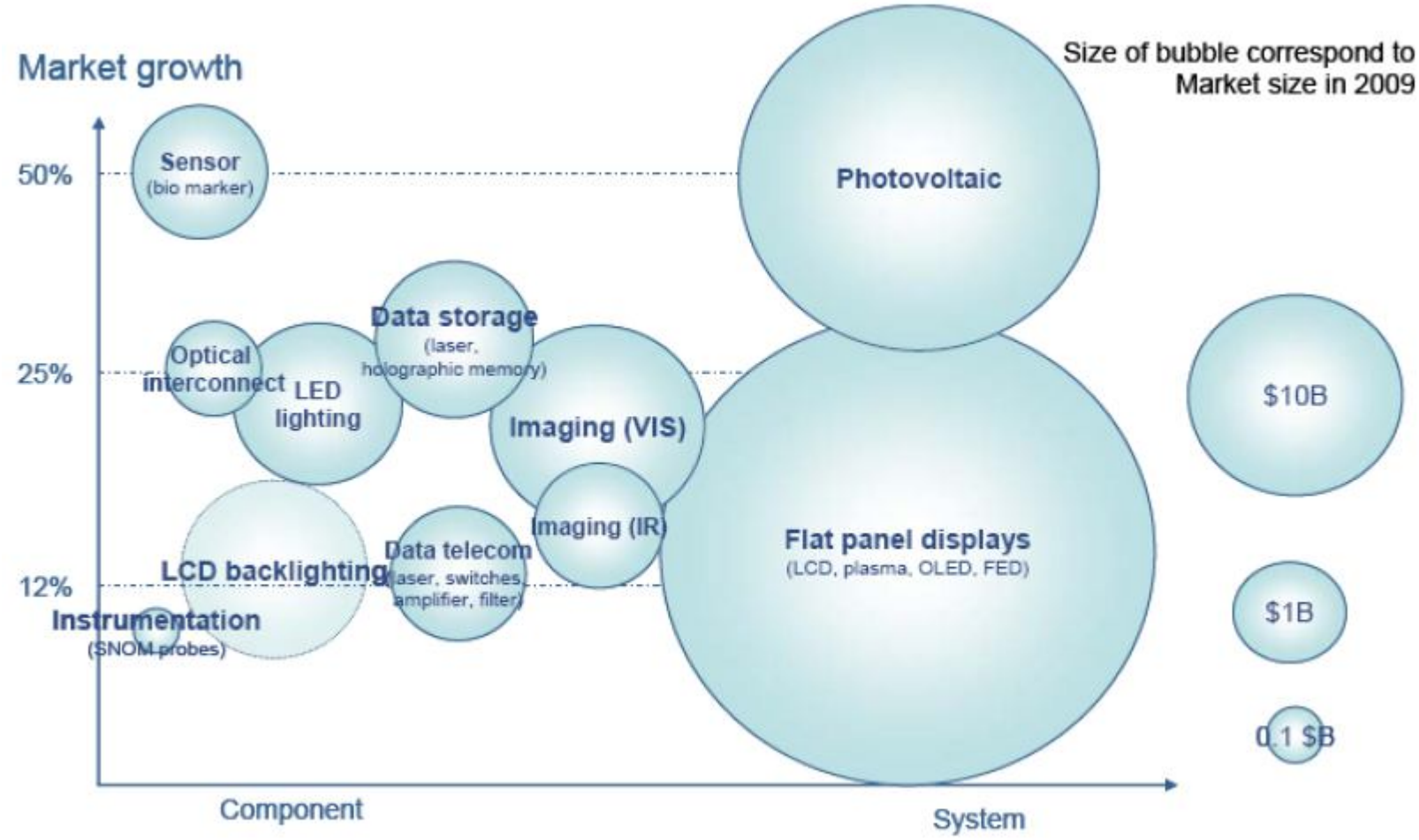
Opportunities by revenue by end products (US $ millions)

Chip interconnects, passive components, lasers

or

Optofluidics and displays?

Nanophotonics Market



MONA Roadmap 2007

Research Trends