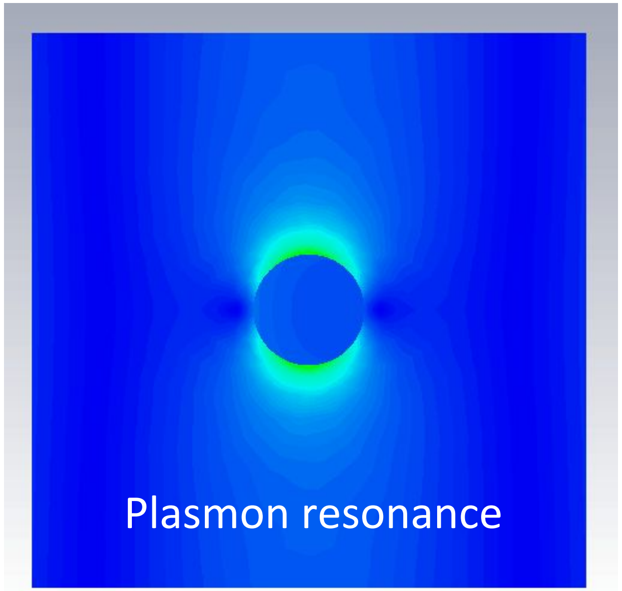
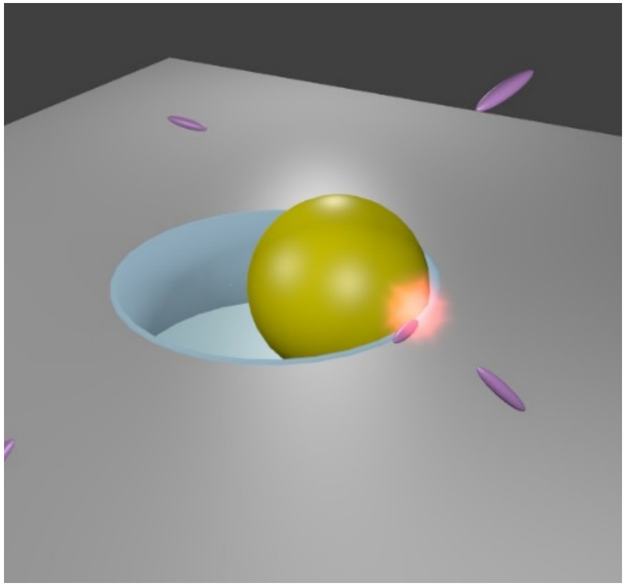
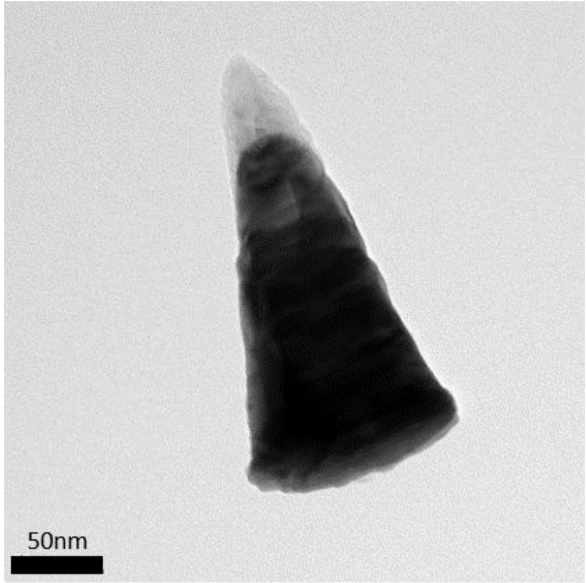
Intro to Nanophotonics:
Plasmonics and applications







Chatdanai Lumdee (Tua)

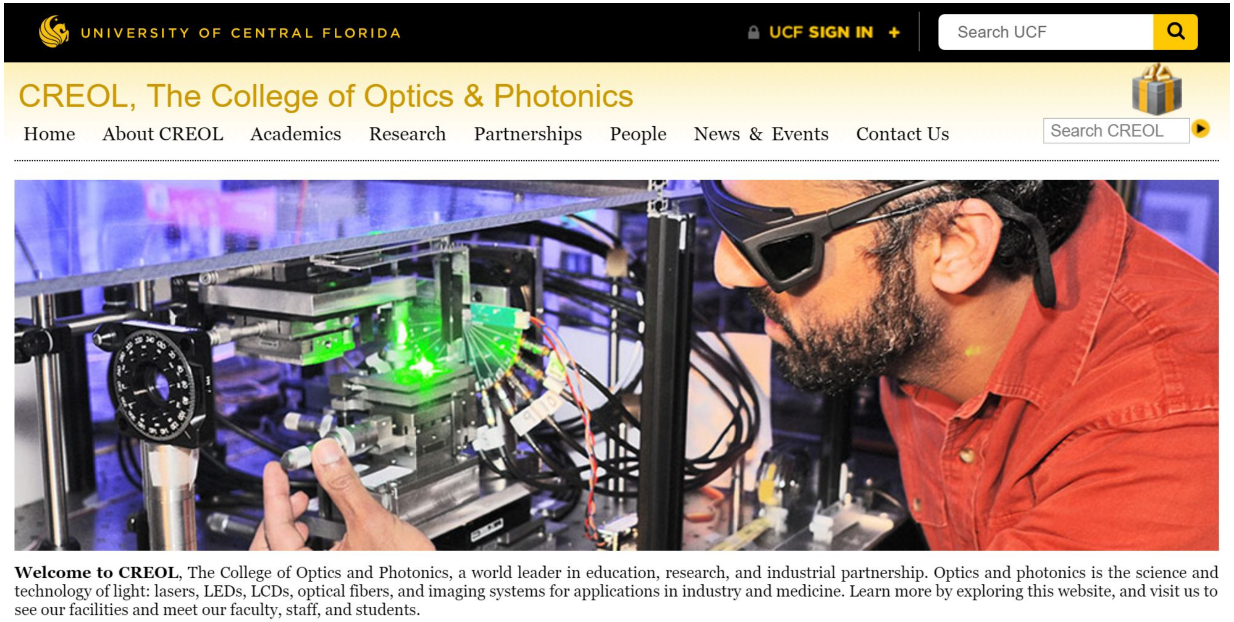
CREOL UCF

Chulalongkorn University
February 2, 2018

CHALMERS UNIVERSITY OF TECHNOLOGY
UNIVERSITY OF GOTHENBURG

Introduction – CREOL

CREOL, the College of Optics and Photonics – www.creol.ucf.edu



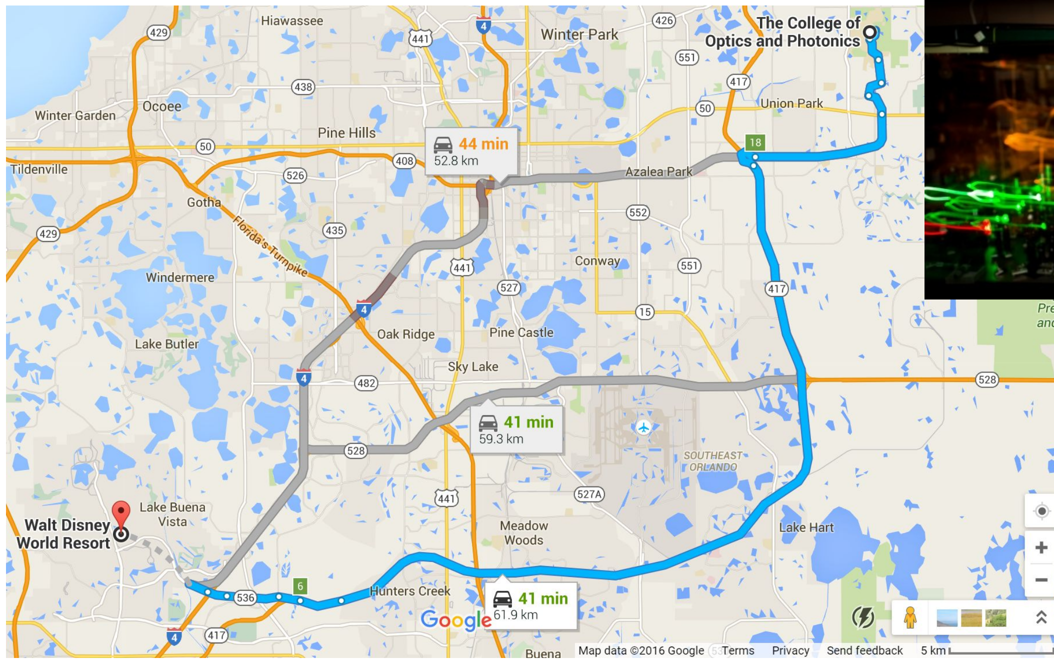
CREOL's trivia

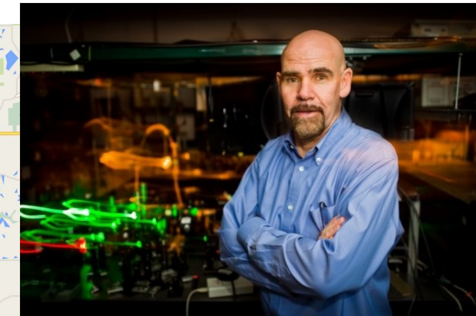
Founded in 1986

34 faculty members,
17 joint faculty members,
6 emeritus professors,
58 research scientists,
137 graduate students, and
90 undergraduate students

Research areas e.g.
display,
imaging,
integrated photonics,
lasers,
optical fibers,
nonlinear and quantum optics,
sensing, …

Introduction – Orlando, FL





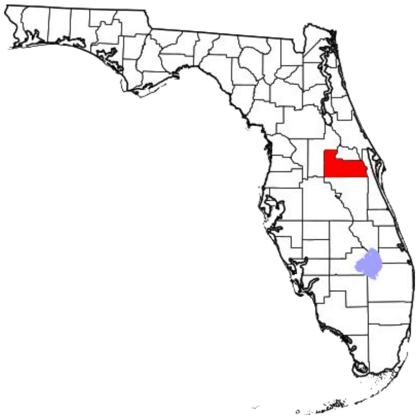
The Walt Disney World Resort

The most visited vacation resort in the world.

The Universal Orlando Resort

The Wizarding World of Harry Potter

Introduction – Orlando, FL



Gothenburg (Swedish: Göteborg)

Introduction –University of Gothenburg/Chalmers

UNIVERSITY OF GOTHENBURG

UNIVERSITY OF GOTHENBURG

CHALMERS

Gothenburg Physics Centre

AVANCEZ 1829

CHALMERS
UNIVERSITY OF TECHNOLOGY

MC2

1240 m^2 of cleanroom classified area

Introduction – Gothenburg, Sweden

Outline

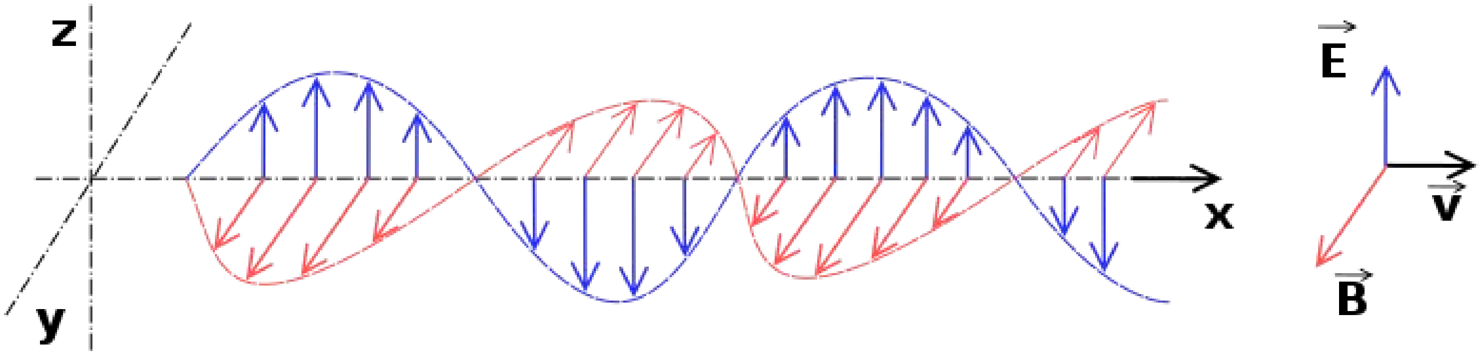
Nanophotonics
- Optics/photonics
- Nano?

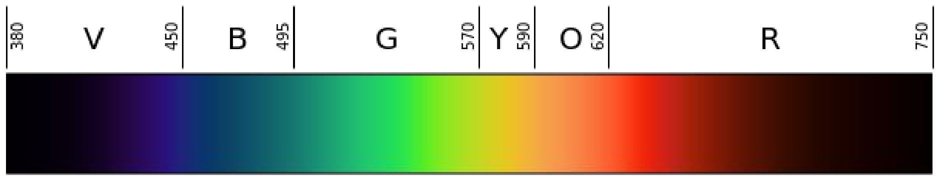
Plasmonics
- Localized surface plasmon resonances
- Surface plasmon polaritons

Examples of applications
- Nanosensors
- Data storage

Optics/Photonics

https://en.wikipedia.org/wiki/Electromagnetic_radiation





James Clerk Maxwell

Maxwell’s equations

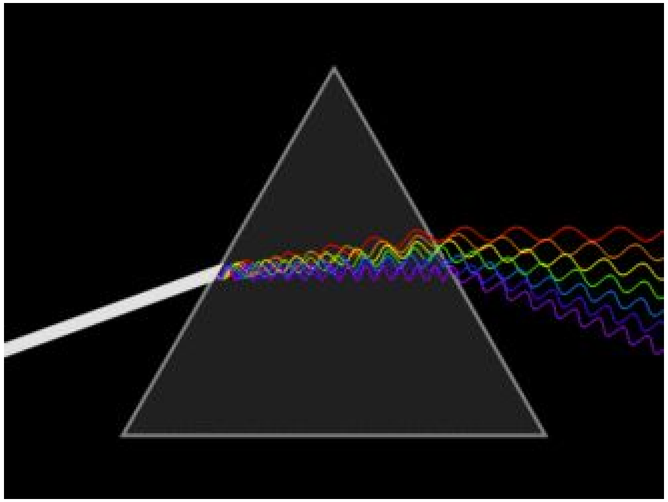
1. $\nabla \cdot \mathbf{D} = \rho_V$

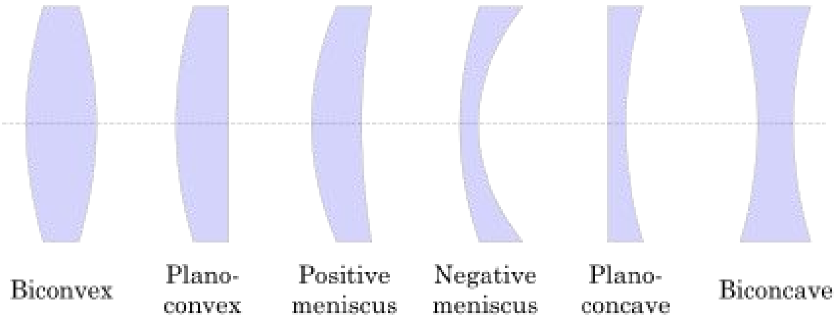
2. $\nabla \cdot \mathbf{B} = 0$

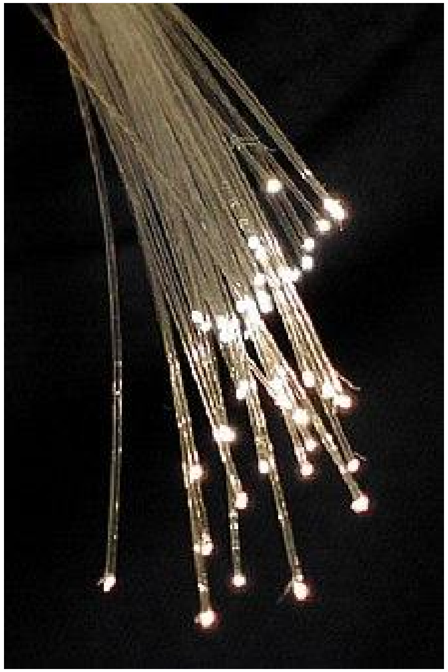
3. $\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t}$

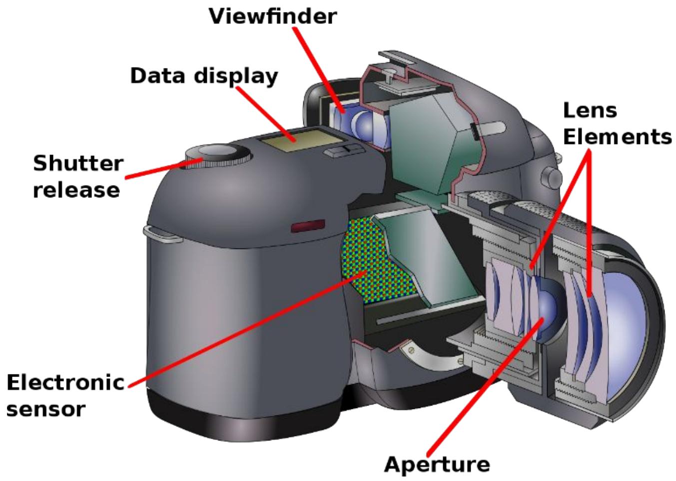
4. $\nabla \times \mathbf{H} = \dfrac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$

Optics/Photonics



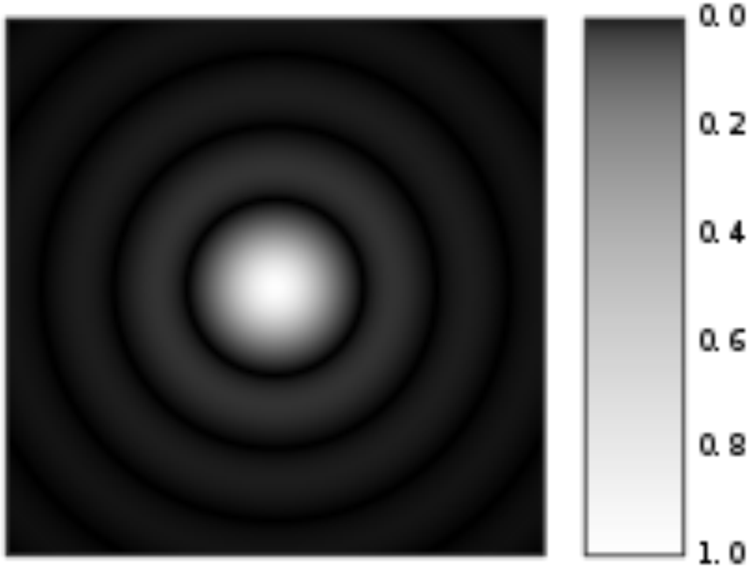




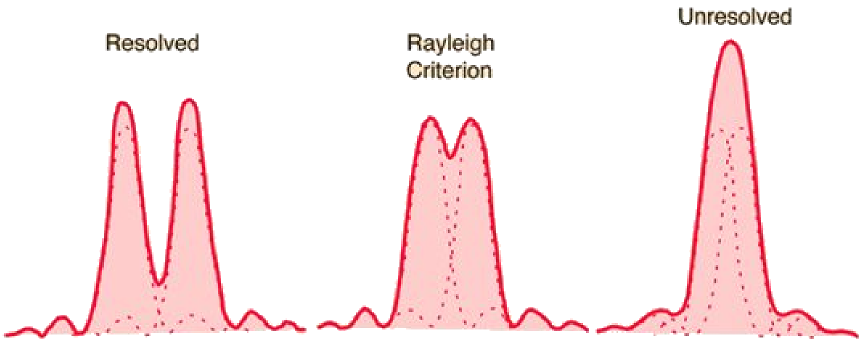


Nano?

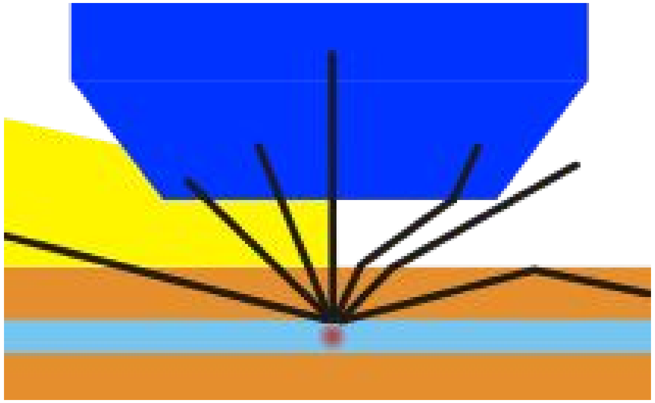
https://en.wikipedia.org/wiki/Airy_disk



http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/diflim.html



https://en.wikipedia.org/wiki/Oil_immersion



https://en.wikipedia.org/wiki/Diffraction-limited_system

Abbe diffraction limit

$$d = \frac{\lambda}{2 \times NA} = \frac{\lambda}{2 \times n \cdot \sin\theta}$$

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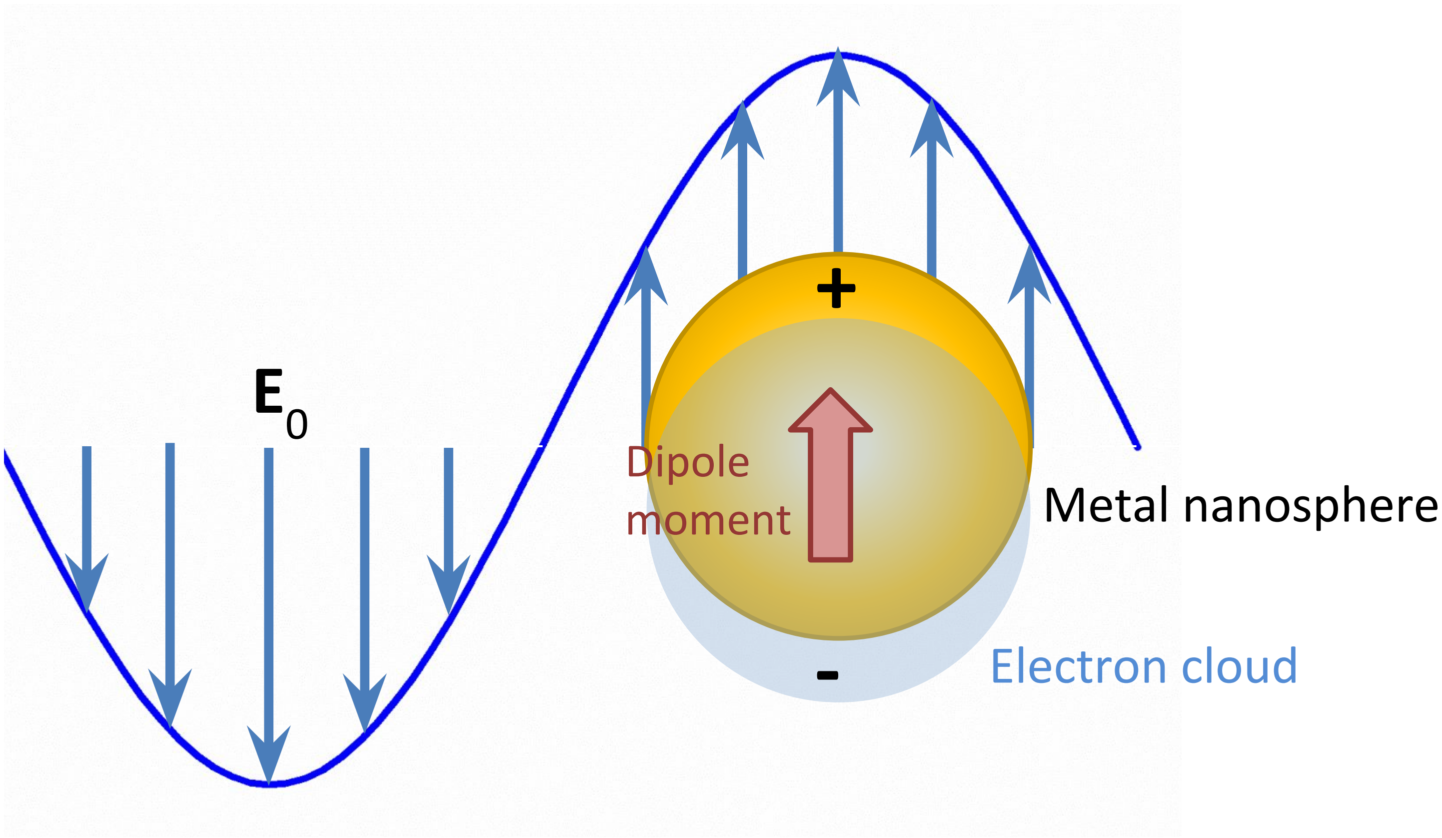
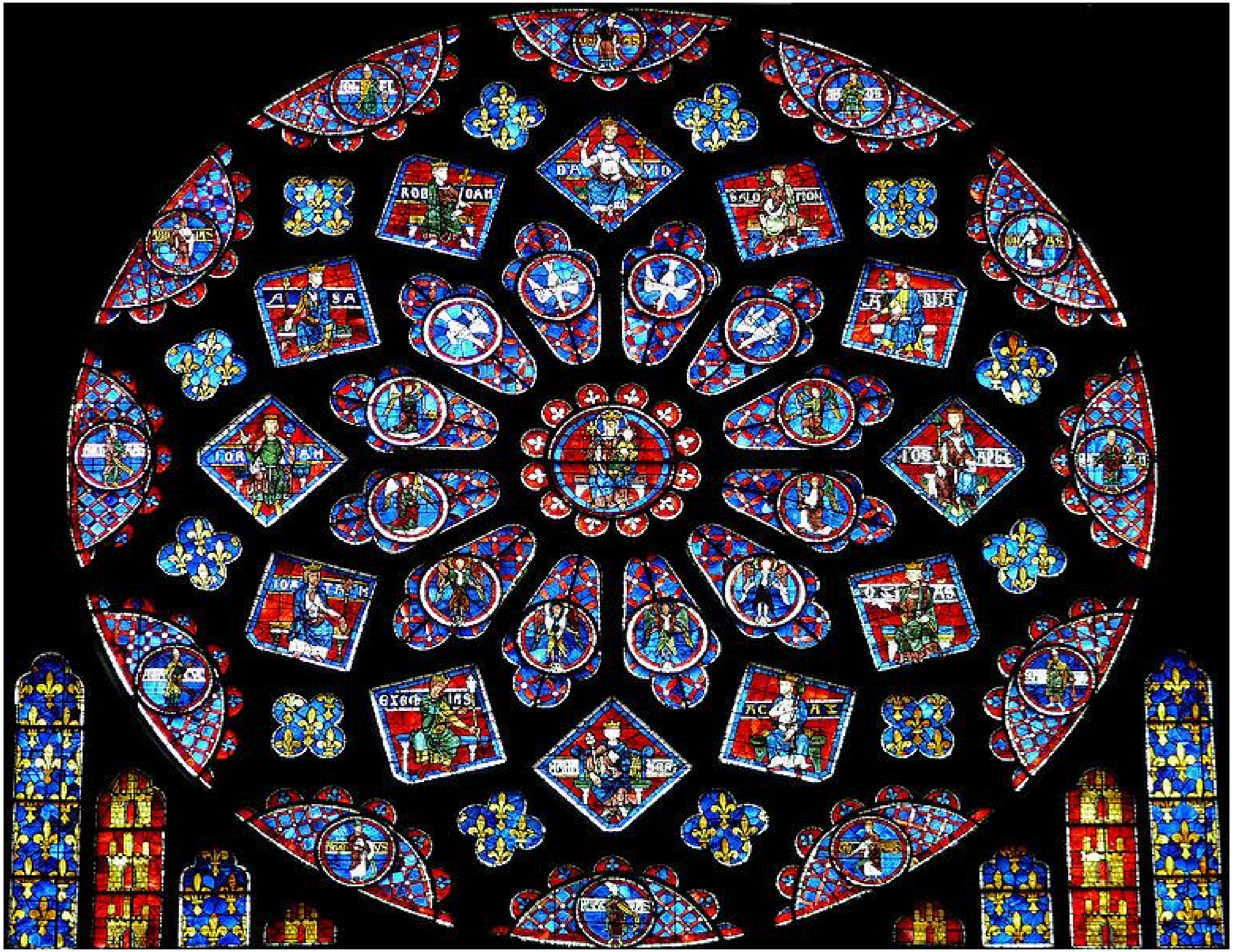
Plasmonics

Plasmon → a collective oscillation of electrons

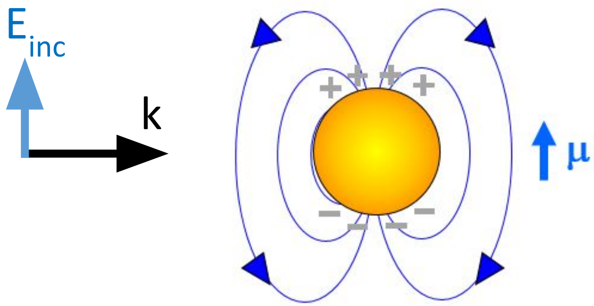


Plasmonics



Colorful windows of churches in medieval age across Europe and even in 4th-century Roman glass.

Single NP in free space



Electrostatic approximation

Particle << wavelength

$$\frac{E_{in}}{E_{inc}} = -3\frac{\epsilon_{out}}{\epsilon_{in} + 2\epsilon_{out}}$$ (Homogeneous)

Boundary conditions

$$\frac{E_{out}}{E_{inc}} = -3\frac{\epsilon_{in}}{\epsilon_{in} + 2\epsilon_{out}}$$ (on NP surface)

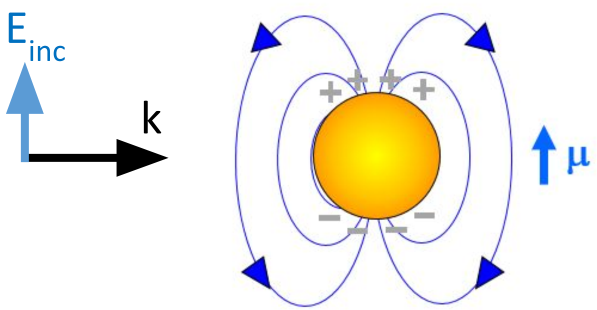
Real metal: $\epsilon_{in}(\omega) = \epsilon'(\omega) + i\epsilon''(\omega)$ $\boxed{E_{in}\ and\ E_{out} \rightarrow \infty}$ $when \quad \epsilon_{in} + 2\epsilon_{out} = 0$

(resonance frequency)

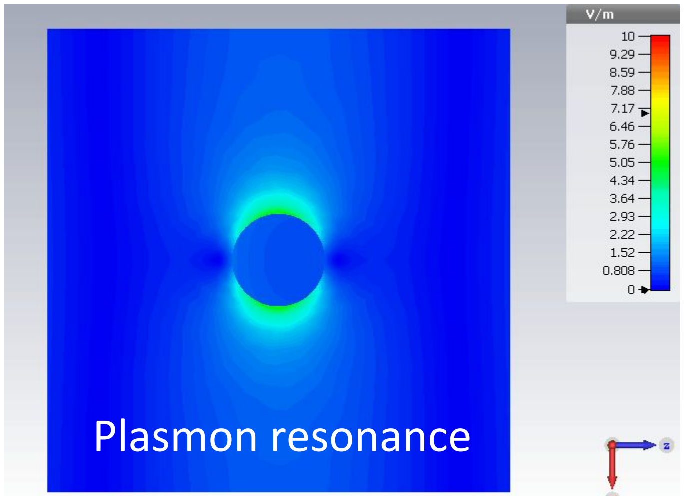
$$\sqrt{\epsilon_{in}(\omega)} = n(\omega) + i\kappa(\omega)$$

Plasmonics

Single NP in free space



50 nm diameter Au NP in water



Frequency domain finite-element simulation

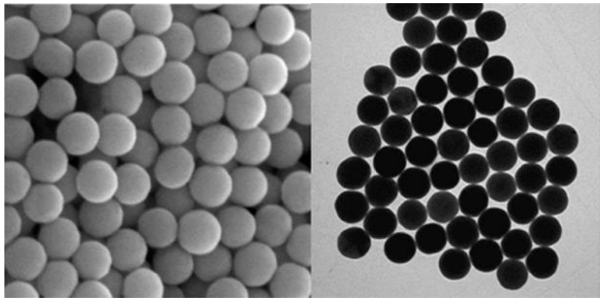
Real metal: $\epsilon_{in}(\omega) = \epsilon'(\omega) + i\epsilon''(\omega)$ $\boxed{E_{in}\ and\ E_{out} \rightarrow \infty}$ $when \quad \epsilon_{in} + 2\epsilon_{out} = 0$

(resonance frequency)

Near-field $\propto \frac{1}{r^3}$ Decays quickly → localized in a nm^3 volume (nanophotonics)

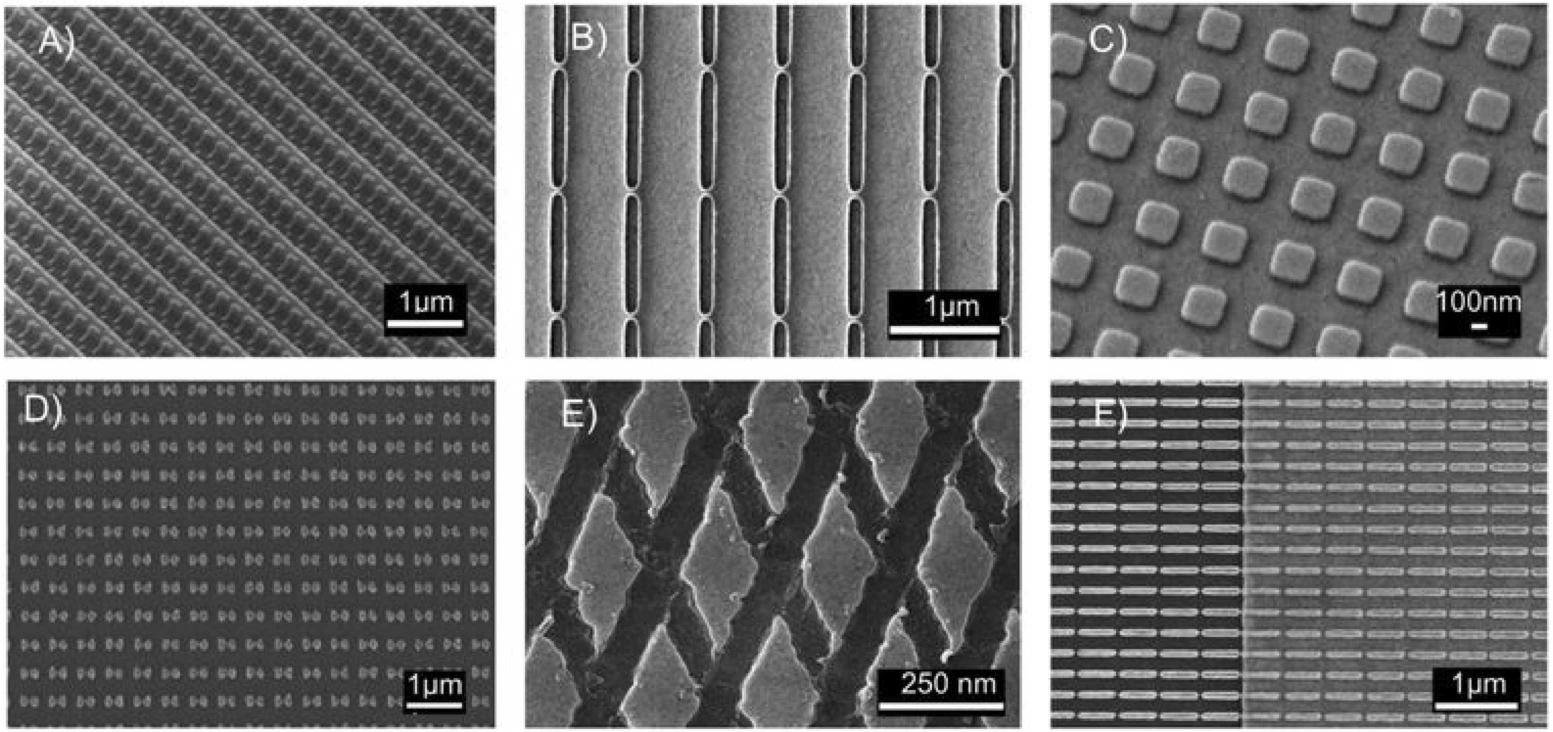
Plasmonics

Simplest form → nanosphere



ACS Nano 7, 11064 (2013)

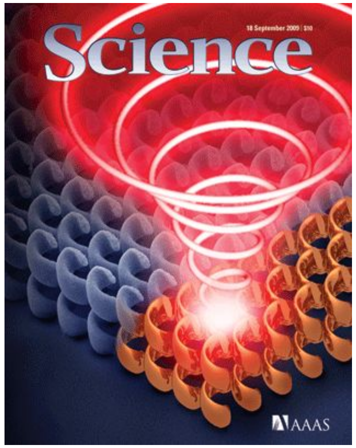
Up to any forms you can imagine



(Review) Analyst (2016), 141, 756

Plasmonics

Science 325, 1513 (2009)

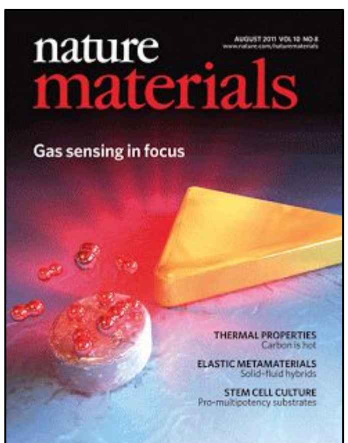


Broadband circular polarizer

Nano Letters 10, 1537 (2010)

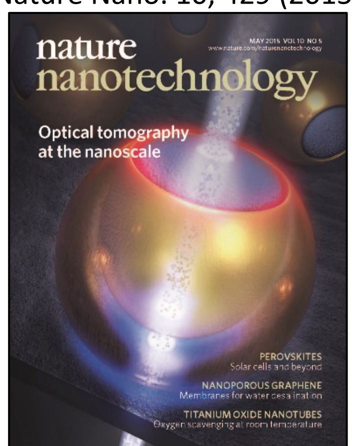
Nanodisk resonators

Nature Mat. 10, 631 (2011)



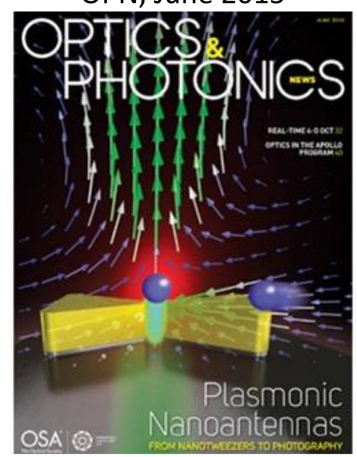
Gas sensor

Nature Nano. 10, 429 (2015)



3D imaging

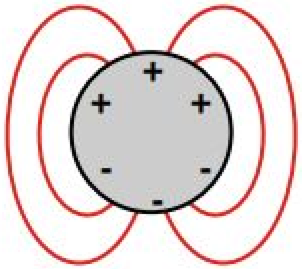
OPN, June 2015



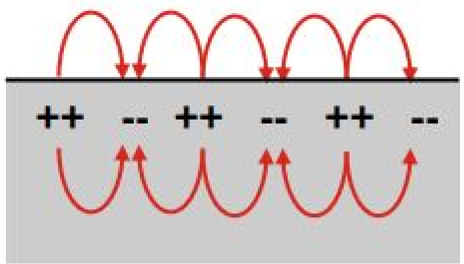
More …

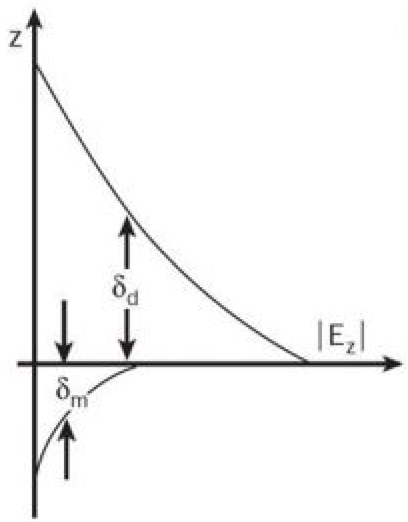
Plasmonics

Metal sphere
localized SPPs



Metal surface





$$k_{spp} = \frac{2\pi}{\lambda_{spp}} = k_0 \sqrt{\frac{\epsilon(\omega)\epsilon_d(\omega)}{\epsilon(\omega) + \epsilon_d(\omega)}}$$

where k_{spp} and k_0 are the SPP and free space wavevectors, and $\epsilon(\omega)$ and $\epsilon_d(\omega)$ are the dielectric functions of the metal and the dielectric film, respectively.

https://www.photonics.ethz.ch/fileadmin/user_upload/Courses/NanoOptics/plasmons2.pdf

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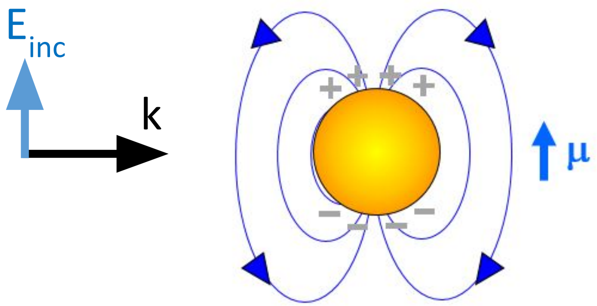
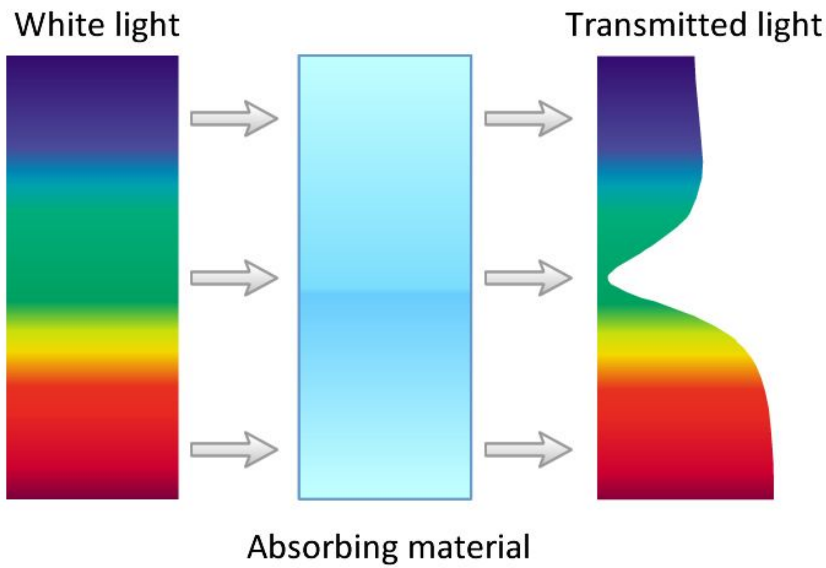
Plasmonics for nanosensors



(resonance frequency)

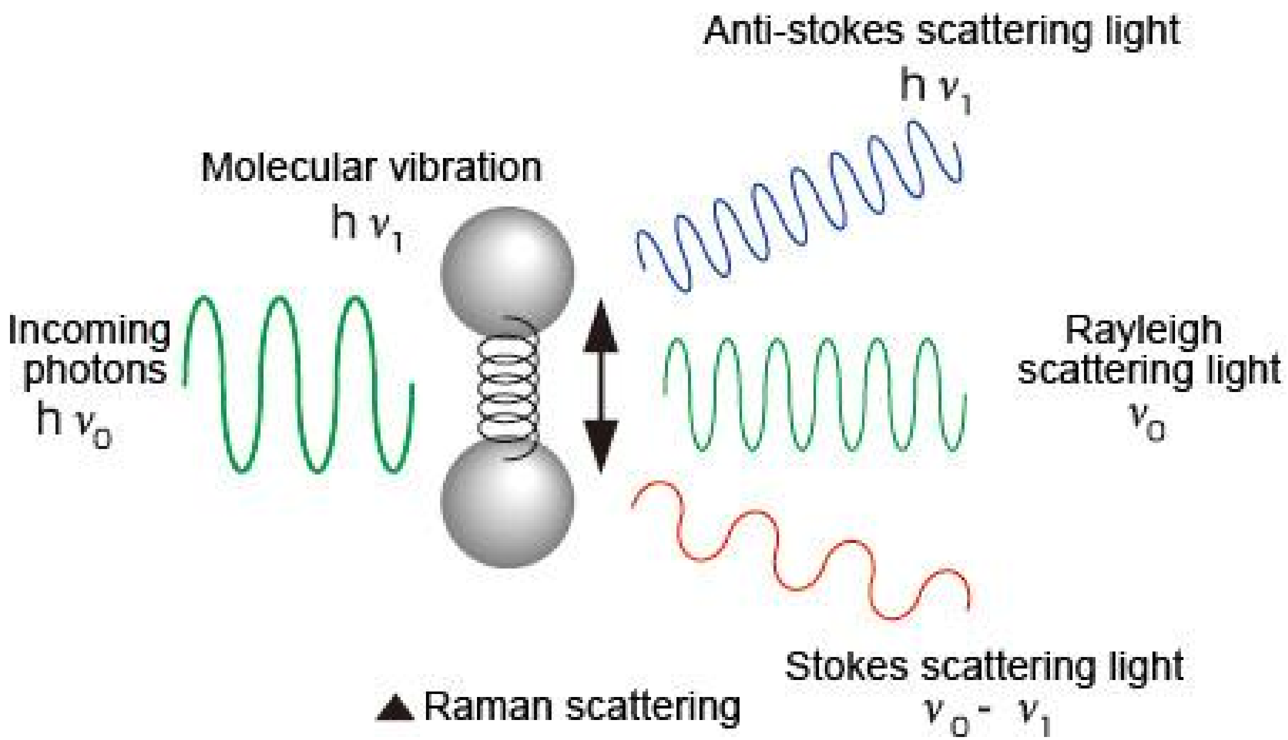
$$\boxed{E_{in}\ and\ E_{out} \to \infty} \quad when \quad \epsilon_{in} + 2\epsilon_{out} = 0$$



https://nanocomposix.com/pages/gold-nanoparticles-optical-properties

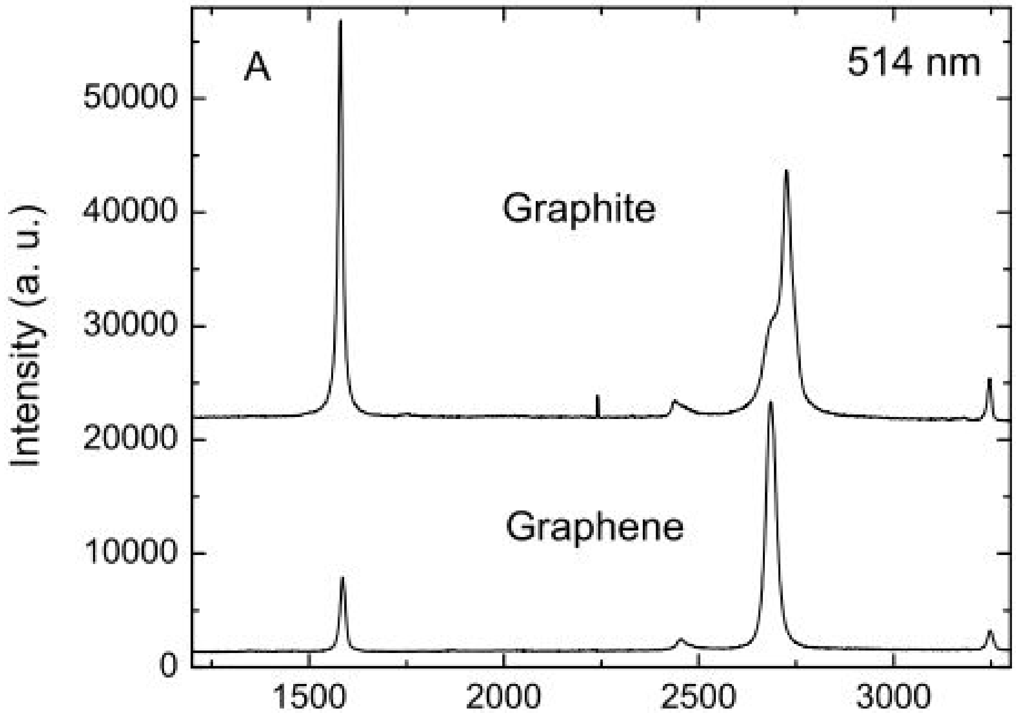
Plasmonics for nanosensors

http://www.hamamatsu.com/eu/en/technology/lifephotonics/environment/SuperiorDetectionOfDiverseChemicals/index.html



Plasmonics for nanosensors

Phys Rev Lett 97, 187401 (2006)



Raman spectra at 514 nm for bulk graphite and graphene

Molecular fingerprint

Challenge

Molecular Raman scattering is a <u>weak</u> process, characterized by cross sections of ~10^{-29} cm^2

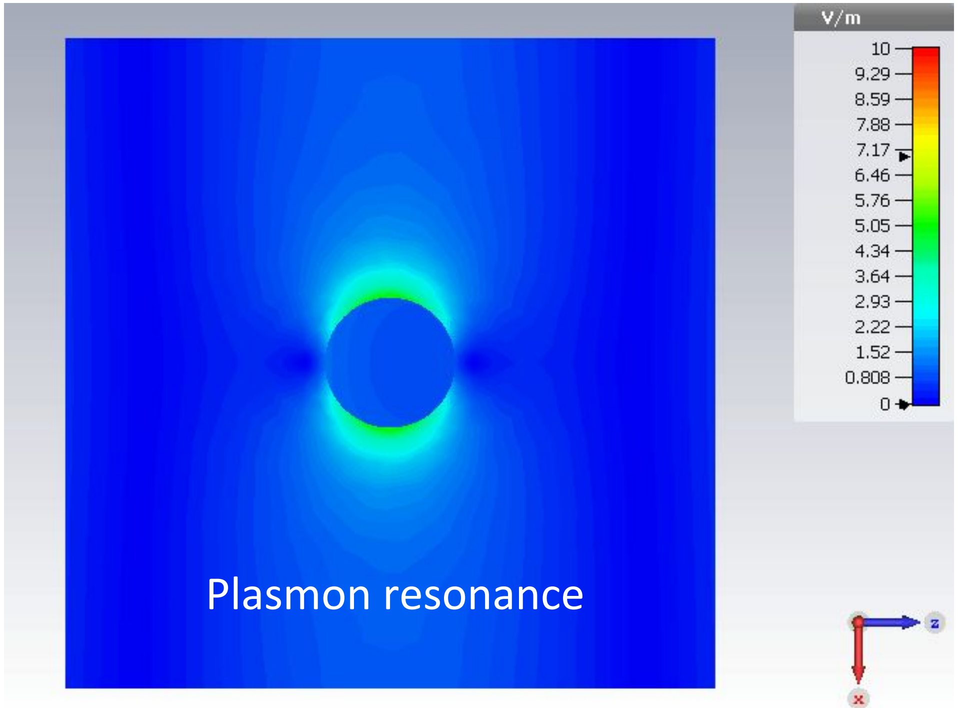
10^{17} photons hitting a 10 nm diameter molecule → one Raman scattering photon out

Plasmonics for nanosensors

$$\frac{E_{out}}{E_{inc}} = -3\frac{\epsilon_{in}}{\epsilon_{in} + 2\epsilon_{out}}$$

$$EF_{SERS} = EF_{excitation} \times EF_{scattering}$$
$$= \frac{|E_{out}(\omega_{ex})|^2 \left|E_{out}\left(\nu_{S/aS} = \omega_{ex} \mp \nu_{vib}\right)\right|^2}{|E_{inc}|^4}$$
$$\approx \left|\frac{E_{out}(\omega_{res})}{E_{inc}}\right|^4$$

50 nm diameter Au NP nm diameter in water

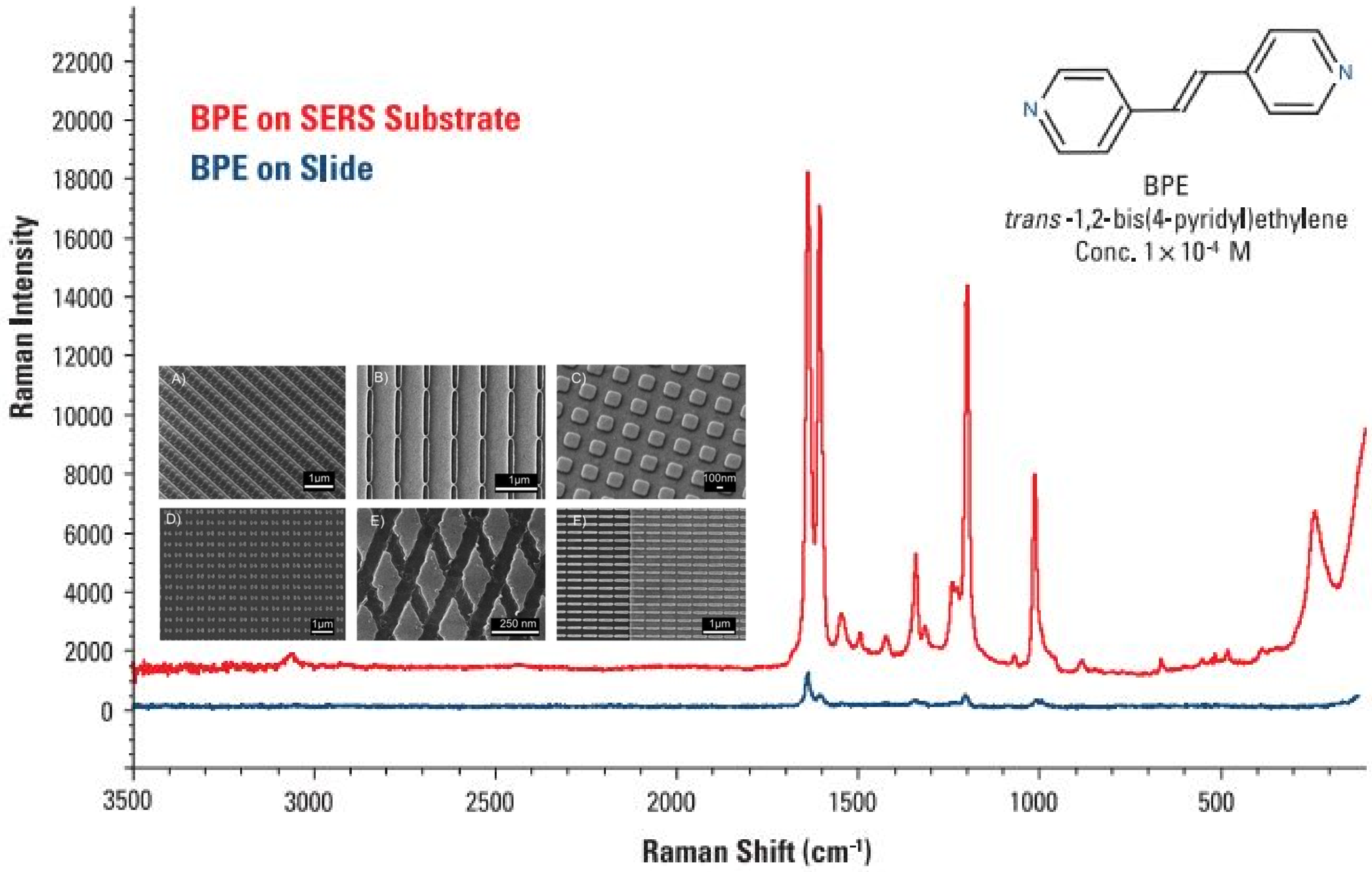


Frequency domain finite-element simulation

Surface enhanced Raman Scattering (SERS)

Plasmonics for nanosensors

Technical Note: 51874, Thermo Fisher Scientific Inc.



Comparison of Raman spectrum of a BPE solution on a plain surface (bottom, blue line) and on a commercial SERS substrate (top, red line) measured at the same conditions

Plasmonics for nanosensors

Probing Single Molecules and Single Nanoparticles by Surface-Enhanced Raman Scattering
Shuming Nie and Steven R. Emory
Science **275**, 1102 (1997);
DOI: 10.1126/science.275.5303.1102

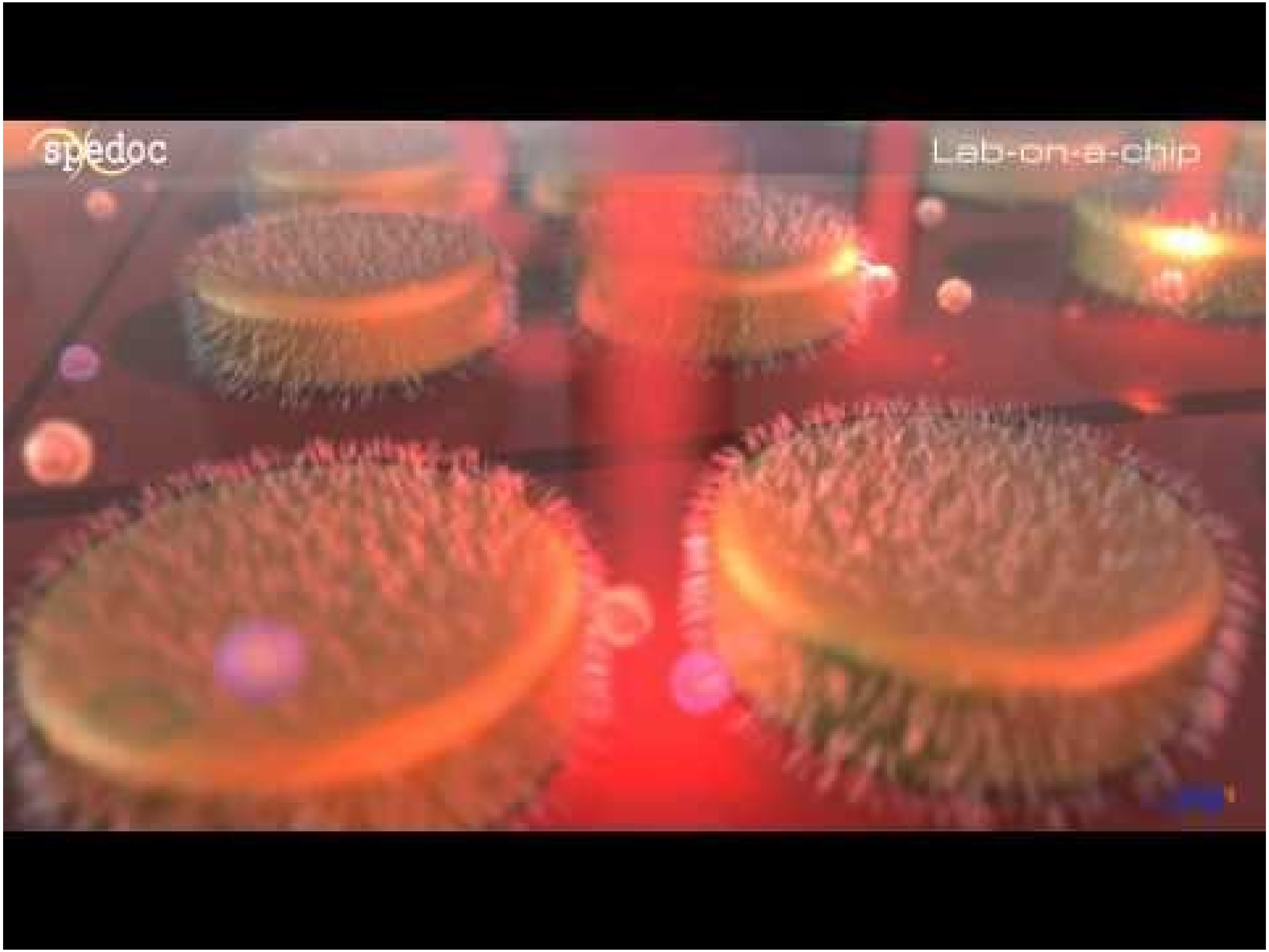
VOLUME 78, NUMBER 9 PHYSICAL REVIEW LETTERS 3 MARCH 1997

Single Molecule Detection Using Surface-Enhanced Raman Scattering (SERS)

Katrin Kneipp, Yang Wang,* Harald Kneipp,† Lev T. Perelman, Irving Itzkan,
Ramachandra R. Dasari, and Michael S. Feld
George R. Harrison Spectroscopy Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
Department of Physics, Technical University of Berlin, D 10623 Berlin, Germany
(Received 6 November 1996)

Note: sensitivity ≠ detection limit

Plasmonics for nanosensors



A new method for early cancer detection -- https://www.youtube.com/watch?v=5GFoH5cwFGQ

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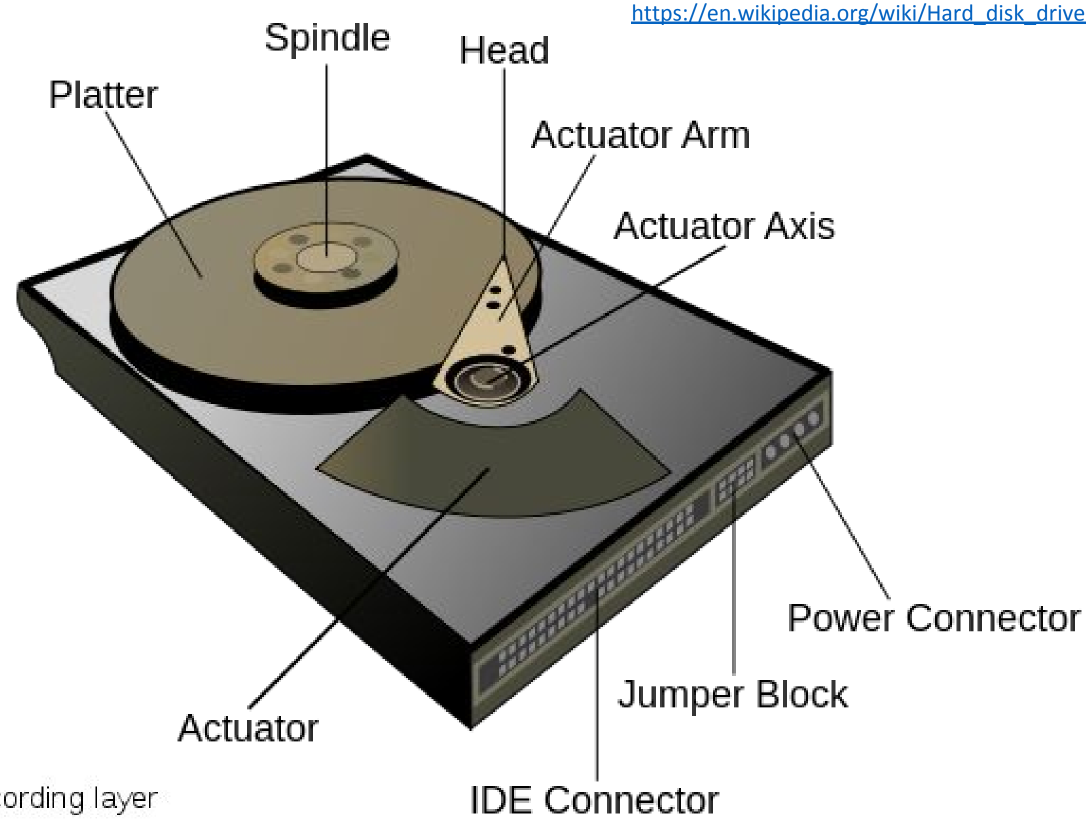
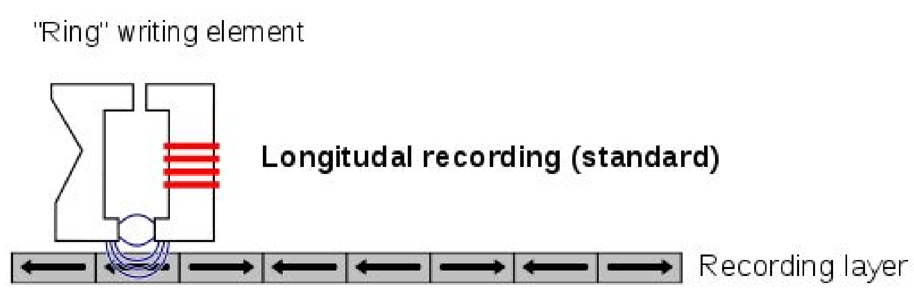
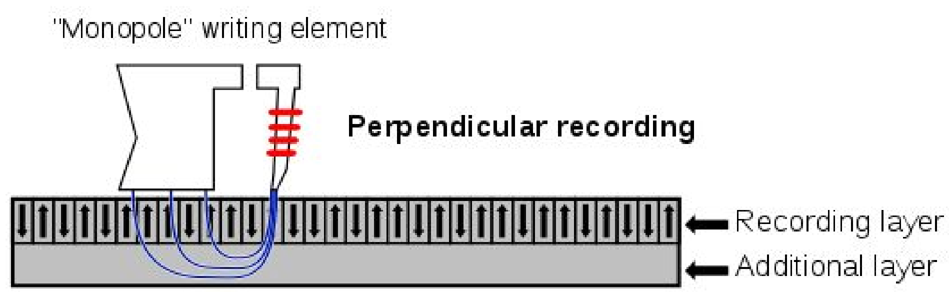
- Nanosensors
- Data storage

Magnetic data storage

https://en.wikipedia.org/wiki/Hard_disk_drive



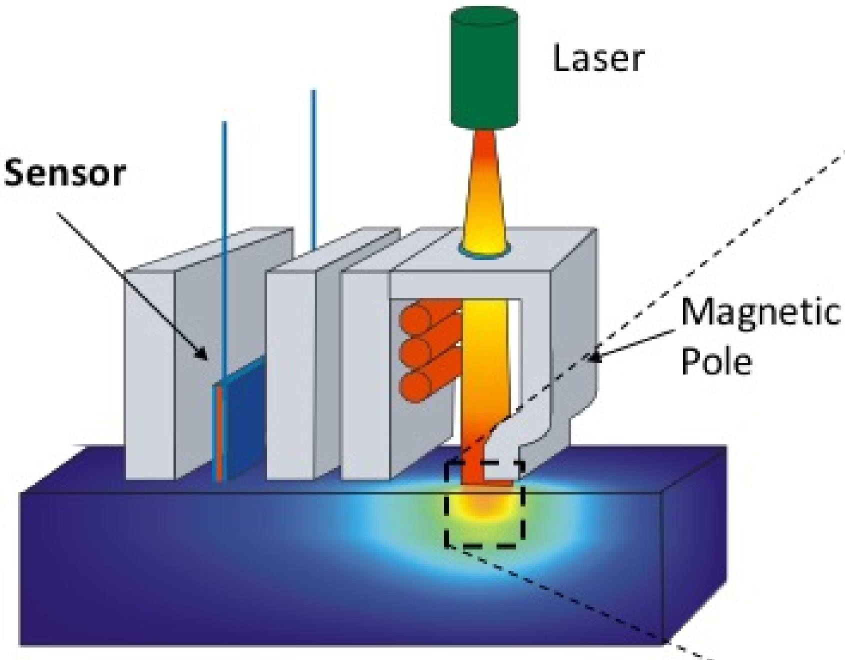


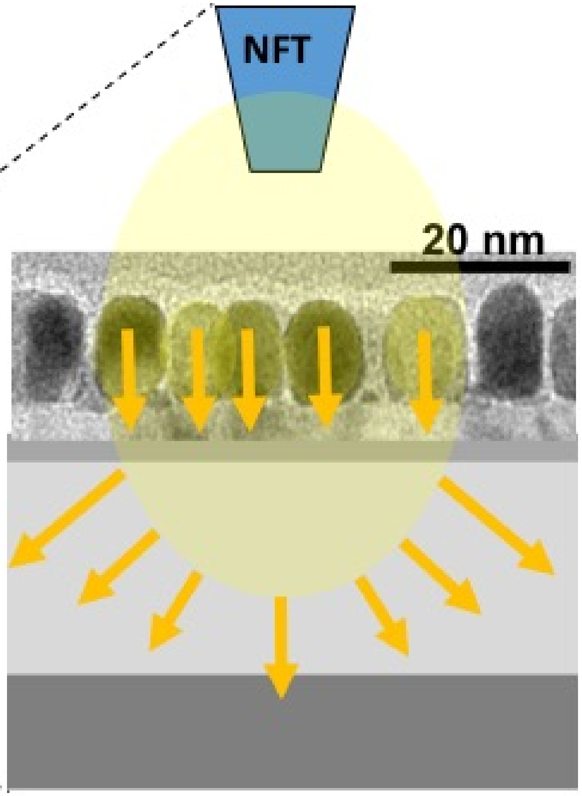


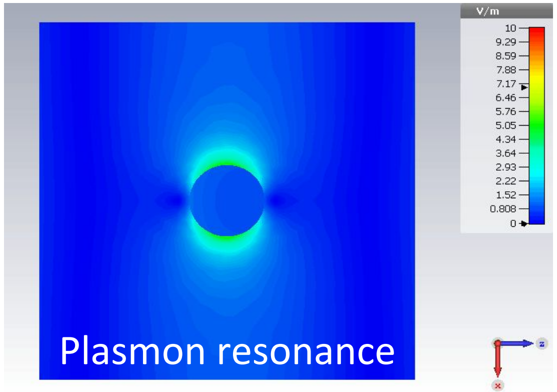
Magnetic data storage

https://www.hzdr.de/db/Cms?pOid=48583&pNid=368

Heat-assisted magnetic recording (HAMR)



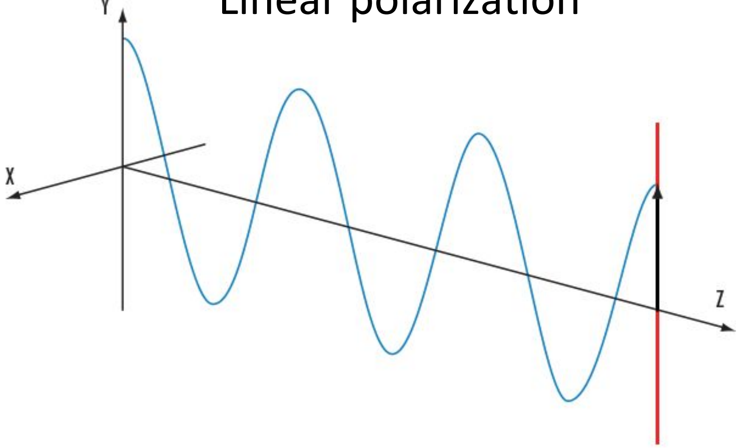




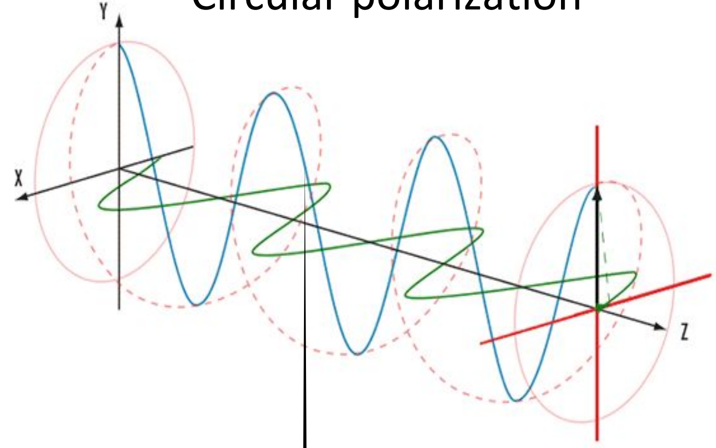
Optical polarization

http://www.edmundoptics.com/resources/application-notes/optics/introduction-to-polarization/

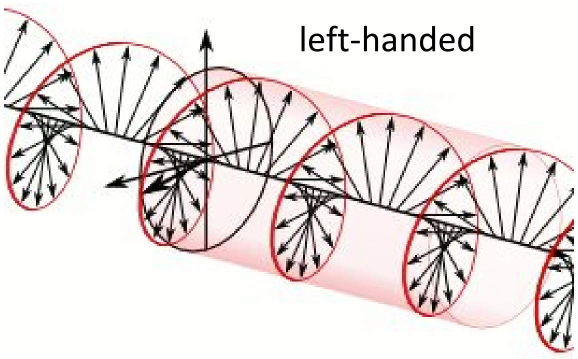
Linear polarization



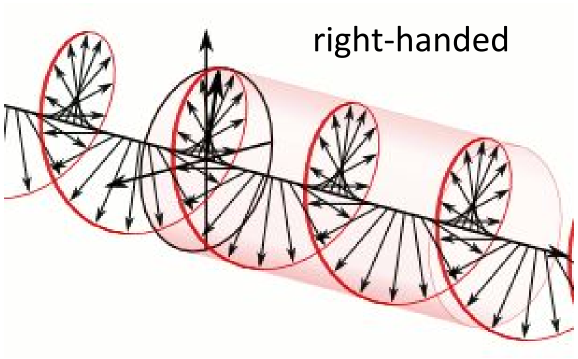
Circular polarization



left-handed



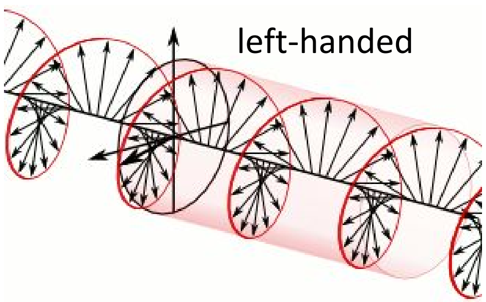
right-handed

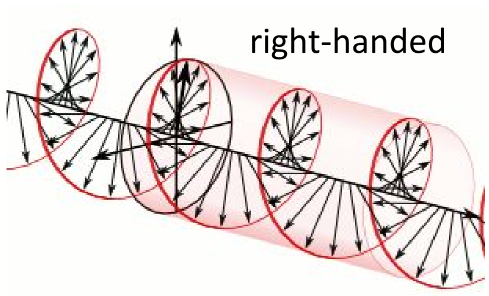


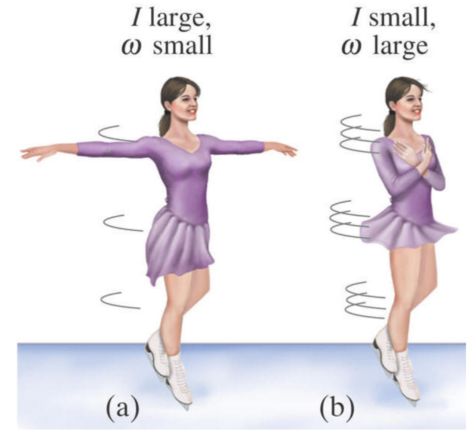
https://en.wikipedia.org/wiki/Circular_polarization

Optical polarization and angular momentum

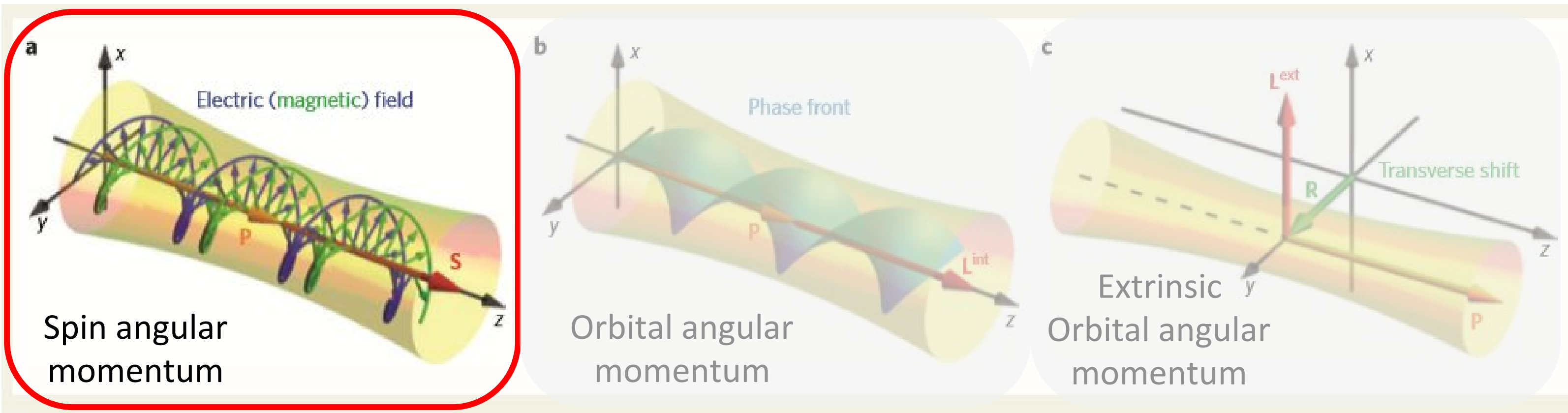
http://ffden-2.phys.uaf.edu/webproj/211_fall_2014/Ariel_Ellison/Ariel_Ellison/Angular.html







Nature Phot. 9, 796 (2015) <review>

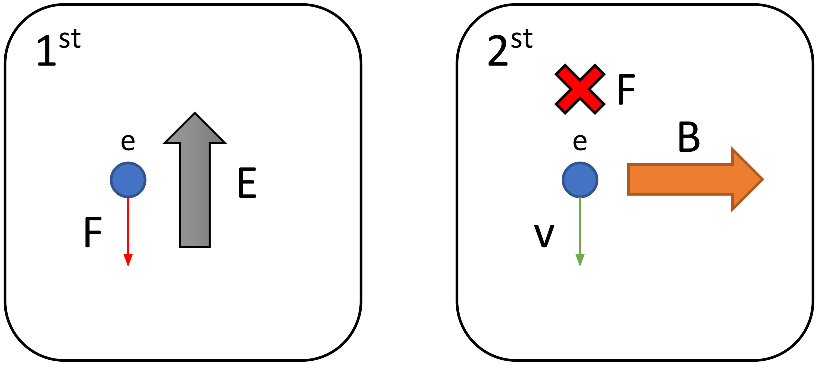


Angular momenta of paraxial optical beams. a, SAM for a right-hand circularly polarized beam with $\sigma = 1$. The instantaneous electric and magnetic field vectors are shown. **b**, IOAM in a vortex beam with $\ell = 2$. The instantaneous surface of a constant phase is shown. **c**, EOAM due to the propagation of the beam at a distance **R** from the coordinate origin.

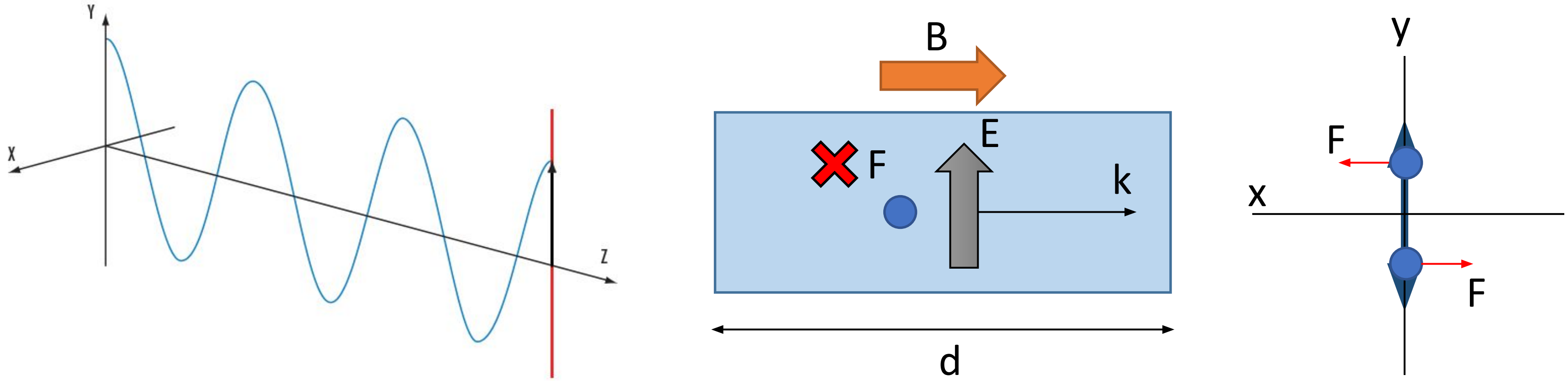
Light and magnetism

Lorentz force

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



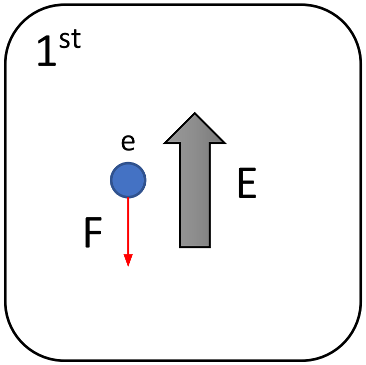
Faraday Effect

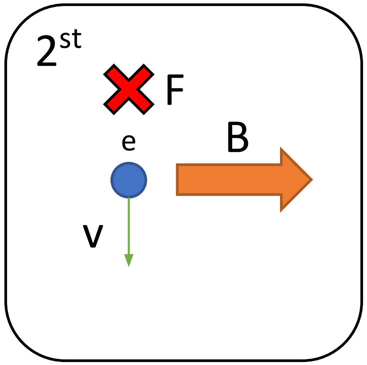


Light and magnetism

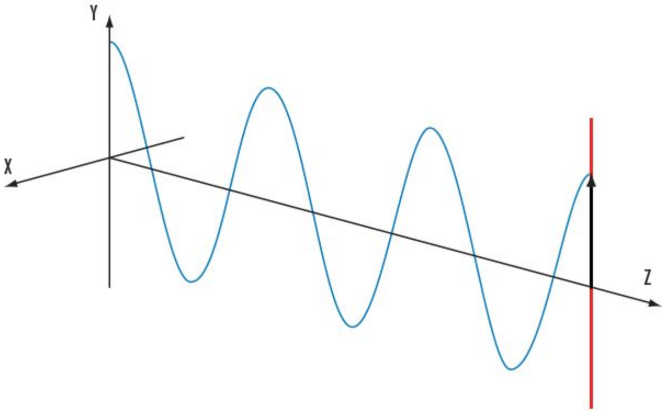
Lorentz force

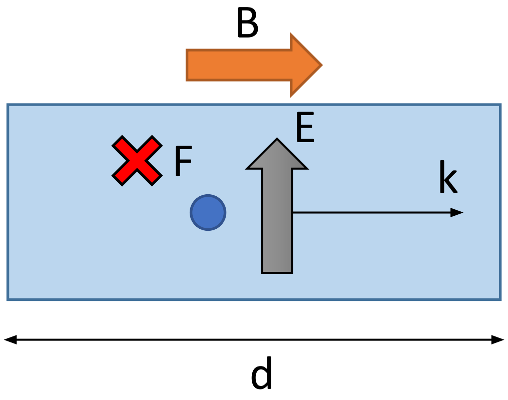
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

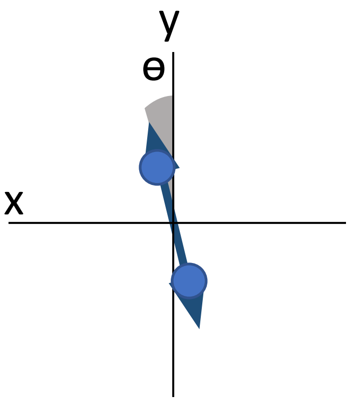




Faraday Effect





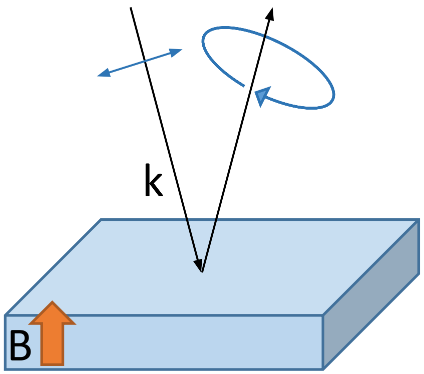


$$\theta = \Upsilon B d$$

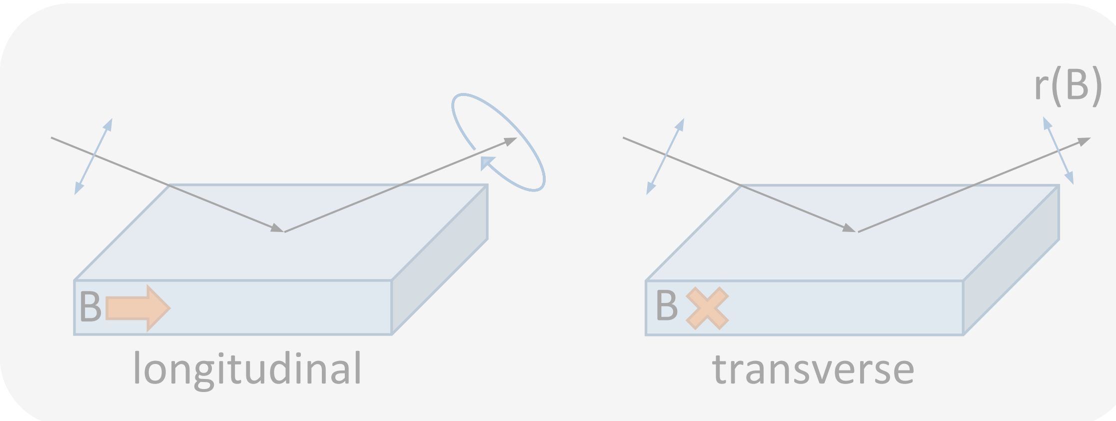
Anisotropy in absorption → elliptical polarized light (ɵ and ε)

Light and magnetism

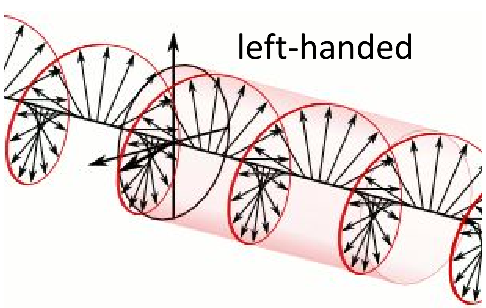
Magneto-optical Kerr effect (MOKE)



polar



Inverse Faraday effect



Science 345, 1337 (2014)

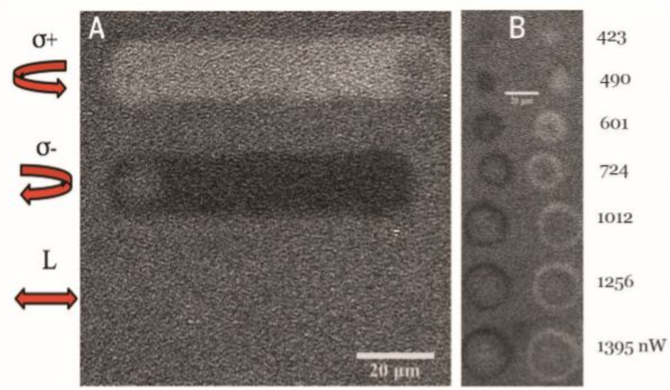
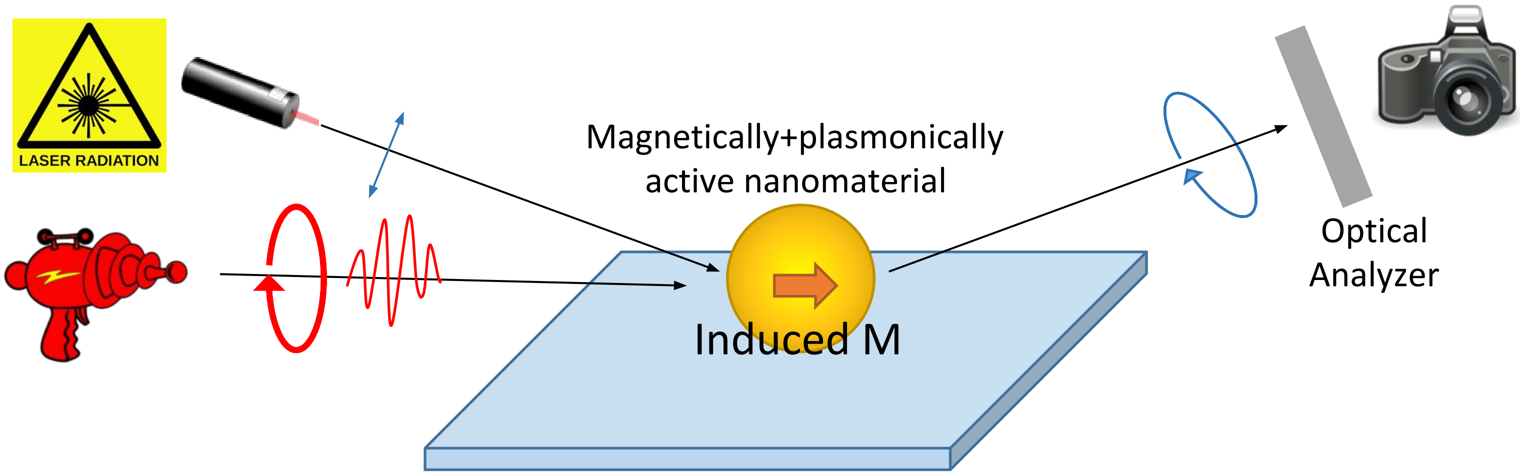
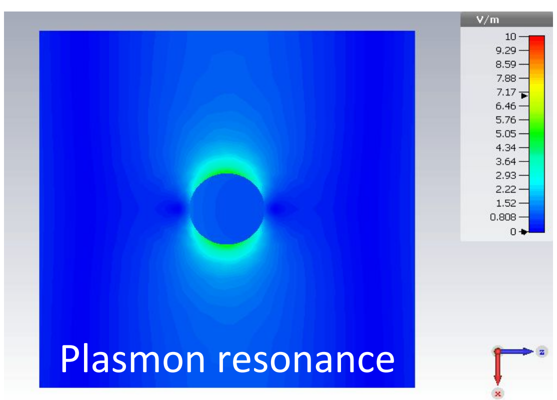


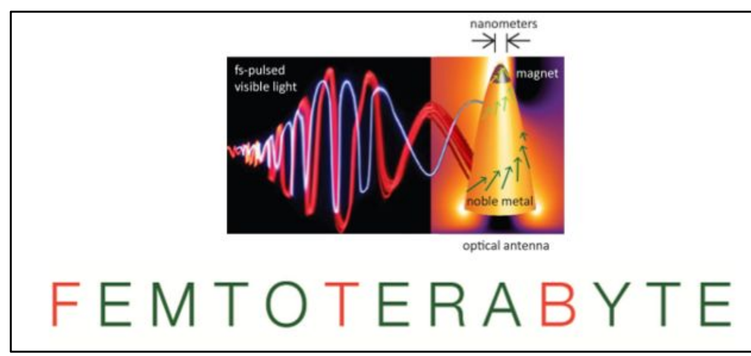
Fig. 3. Magneto-optical response in zero applied magnetic field of a 15-nm FePtAgC granular film sample starting with an initially demagnetized sample. (**A**) Line scans for σ^+, σ^-, and linear polarized light (L). The laser beam was swept over the sample, and the magnetization pattern was subsequently imaged. (**B**) Images of magnetic domains written by keeping the laser spot at a fixed position on the sample. The laser was either σ^+ polarized (left column) or σ^- polarized (right column). The laser power is given next to the image.

Quadratic magnetic rotation, Voigt effect, Zeeman effect, …

Plasmonics for smaller and faster magnetic data storage

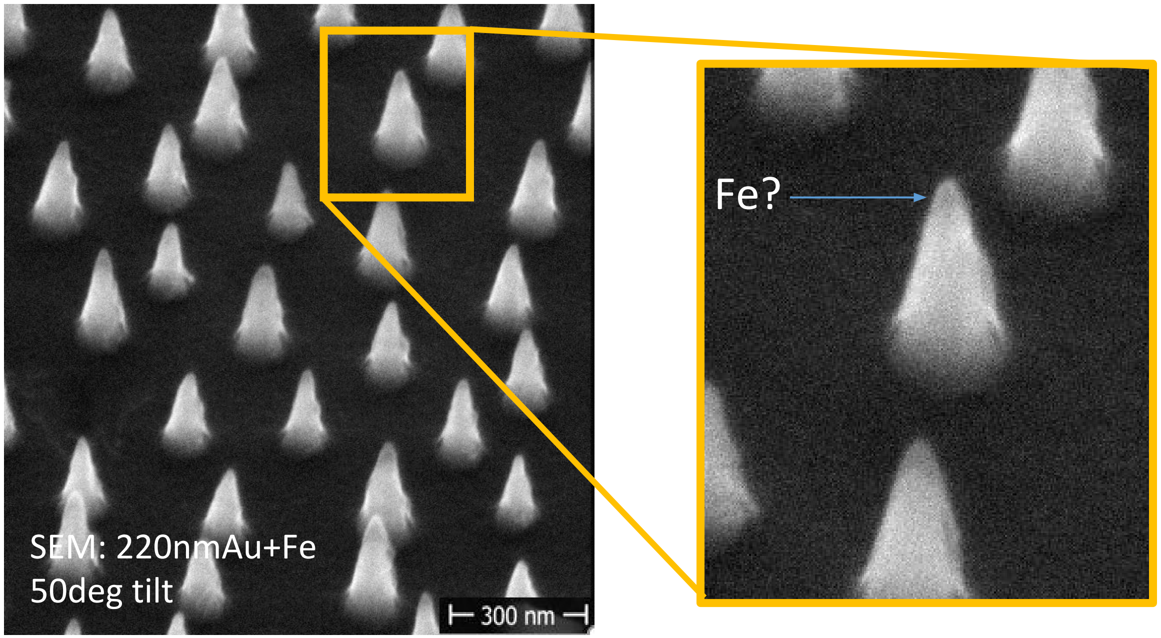


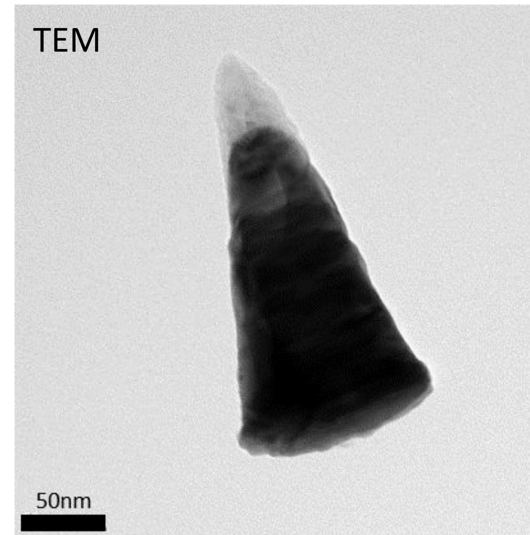




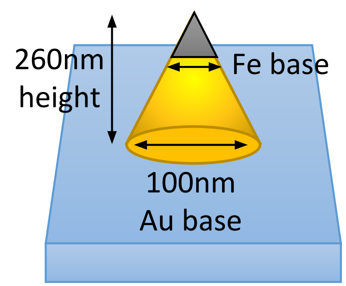
Hybrid metallic-magnetic nanostructures

Sample characterization





Further statistical and chemical analysis needed.
Preliminary (from AFM): 260nm total height

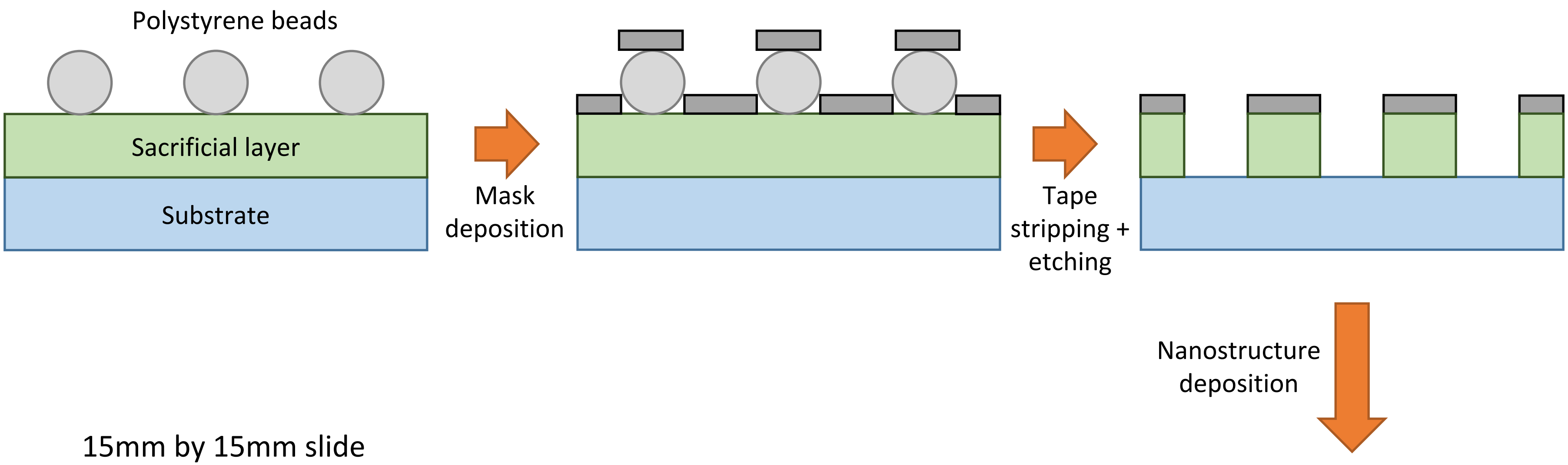


Deduce Fe base and equivalent Fe thickness from geometry and density (AFM+SEM)

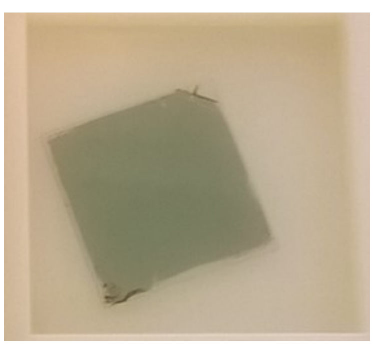
Hybrid metallic-magnetic nanostructures

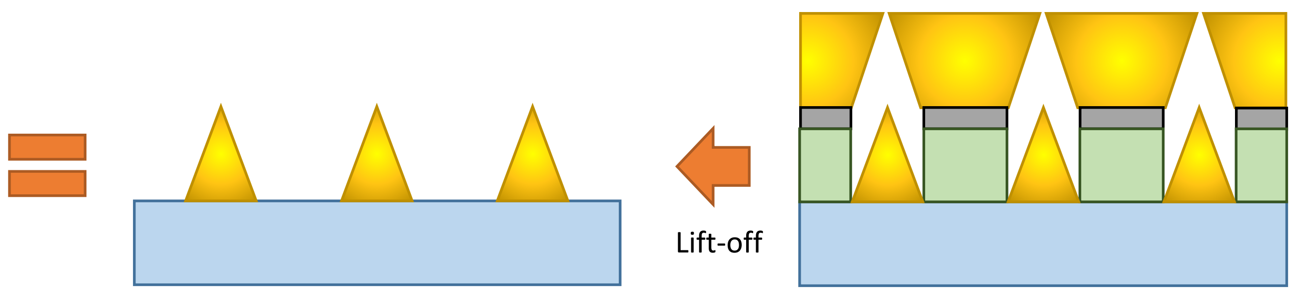
Fabrication process: Hole-Mask Colloidal Lithography

Adv. Mat. 19, 4297 (2007)



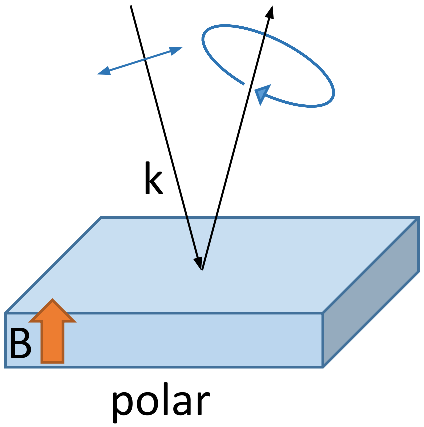
15mm by 15mm slide
(100nm base Au nanocones)

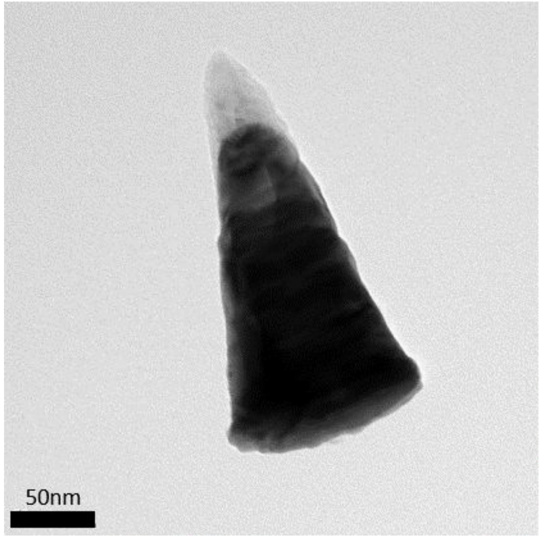


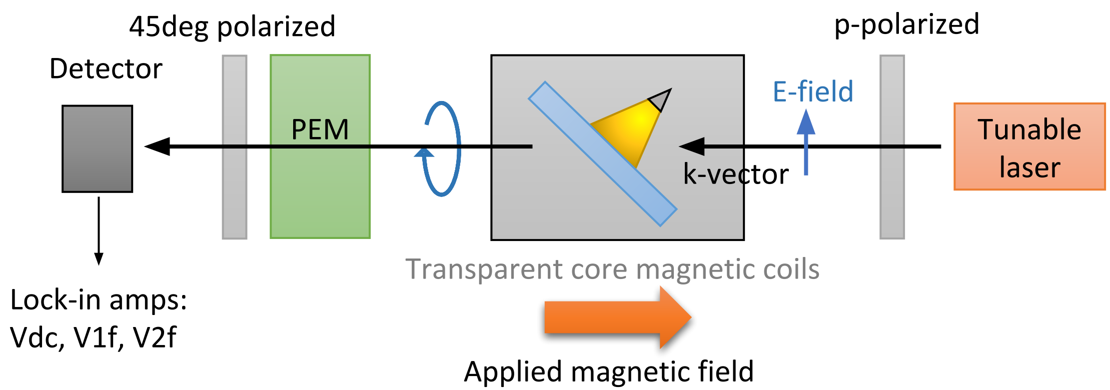


Plasmon-induced MOKE

Magneto-optical Kerr effect (MOKE)

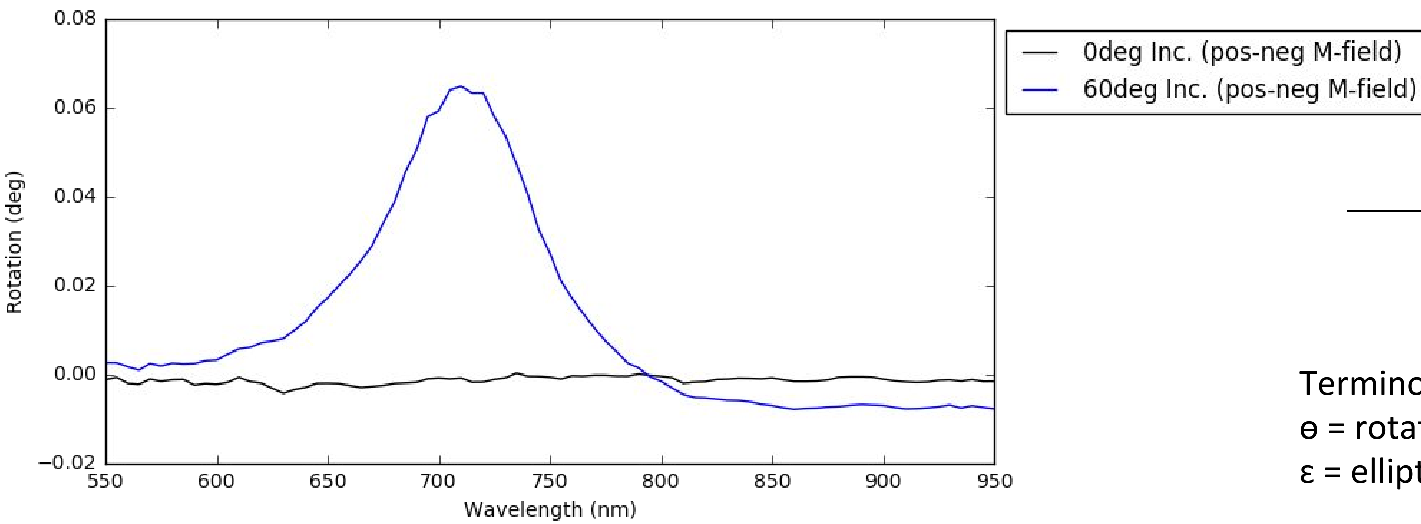


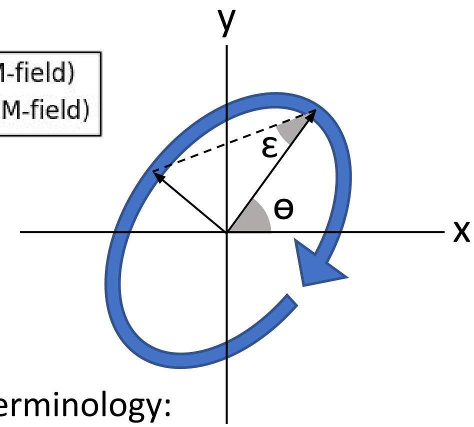




Plasmon-induced MOKE

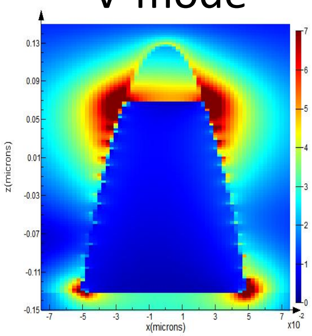
175nm Au cones with Fe tip: absolute rotation

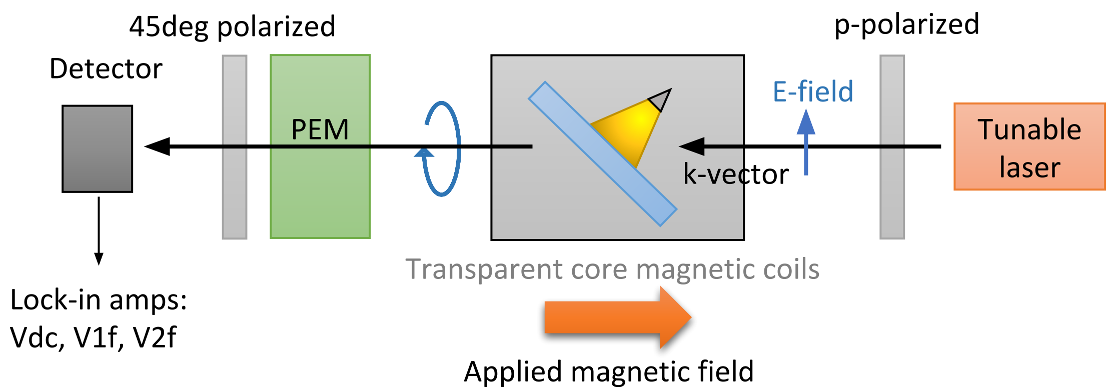


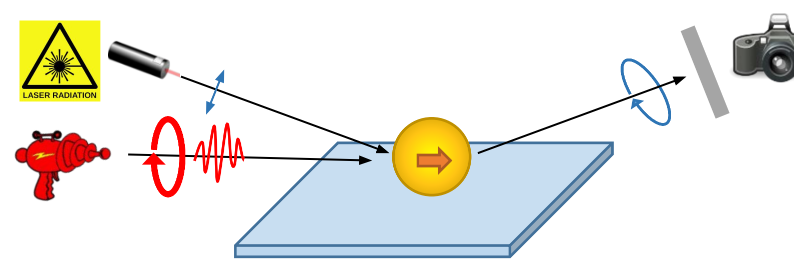


Terminology:
ɵ = rotation,
ε = ellipticity (and handedness)

V-mode







Next is to test ‘nanoscale’ inverse Faraday effect

Summary

Nano-optics/nanophotonics → light-matter interactions at the nanoscale

Plasmonics has played a key role in bridging the two fields

Several potential applications e.g. nanosensors and data storage