Introduction to Nanophotonics

Kent D. Choquette
Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
choquett@illinois.edu

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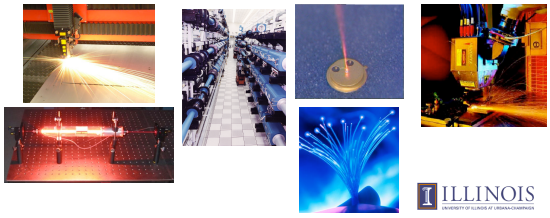
What is Photonics?

Photonics is the generation, transmission, modulation, switching, amplification, signal processing, storage, and detection of light.

The word "photon" denotes the fundamental unit of light, which is both a wave and a particle.



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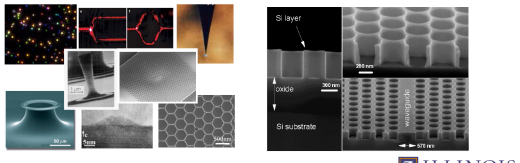
What is Nanophotonics?

Nanophotonics is defined as "the science and engineering of light–matter interactions that take place on wavelength and subwavelength scales of light where the physical, chemical or structural nature of natural or artificial nanostructured matter controls the interactions"

– National Academy of Science



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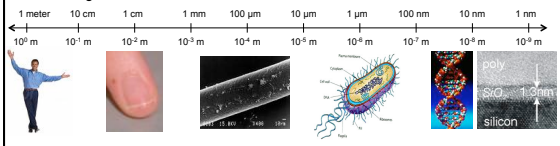
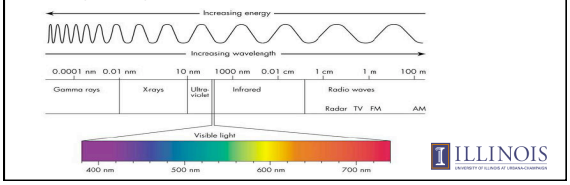
Getting calibrated to nanometer

Matter length Scale



Electromagnetic length scale



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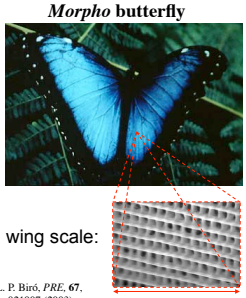
Nanophotonics in nature

***Morpho* butterfly**

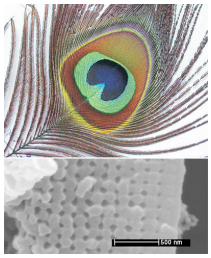


wing scale:

6.21μm

L. P. Biró, *PRE*, **67**, 021907 (2003)

Peacock feather



J. Zi, *Proc. Nat. Acad. Sci. USA*, **100**, 12576 (2003)

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Nanophotonics Outline

1. Light/matter interaction
2. Confinement
   - A. Dielectric
   - B. Periodic
   - C. Metallatic
3. Metamaterials
4. Summary

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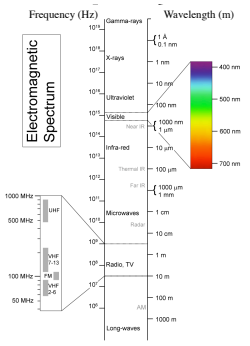
Optical units



Wavelength (λ)

1 nm = 10^{-9} cm

1 μm = 1000 nm

Energy

$h\nu$ (in eV) = $\frac{1.24}{\lambda \text{ (in } \mu\text{m)}}$

Frequency (ν)

ν (in Hz) = $\frac{c}{\lambda}$

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Nanophotonics relative to wavelength

a<<λ.
Effective medium description using Maxwell equations with μ, ε, n, Z

Example:
Optical crystals
Metamaterials

a~λ.
Structure dominates. Properties determined by diffraction and interference

Example:
Photonics crystals
Phased array radar
X-ray diffraction optics

a>>λ.
Properties described using geometrical optics and ray tracing

Example:
Lens system
Shadows

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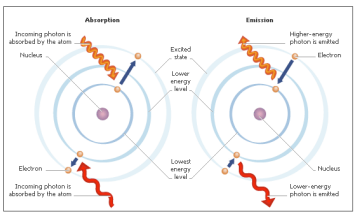
Light matter interaction

Matter consists of the nucleus (protons & neutrons) surrounded by electron cloud. E&M radiation that interacts with nucleus requires very high energy (gamma rays). So light (X-ray to infrared) interacts only with electron cloud.

For transparent materials, light exites an electron cloud of one atom, which "emits" the photon that interacts with another electron cloud, etc. The photon moves at velocity c, but the extra time for the excitation/emission slows the process down to velocity v, so we define the *refractive index*, n = c/v.



For opaque materials, light can also be absorbed and emitted by a resonant electron and photon interaction.

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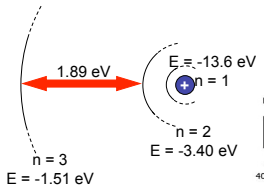
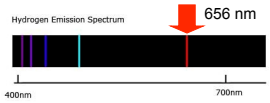
Atomic absorption & emission

In 1913, Niels Bohr proposed that the H-atom electron is confined to specific orbits - quantization

$$E_n = \frac{m_e q^4}{2(4\pi\varepsilon_0 \hbar n)^2} = \frac{-13.6\,eV}{n^2} \qquad n = 1,2,3,\ldots$$



E = 1.89 eV so the wavelength is:
λ = 656 nm



Discrete (single) atoms exhibit energy levels

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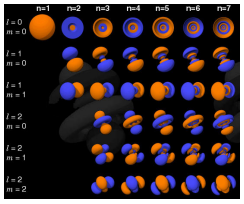
What is an electron?

An electron is a subatomic *elementary* particle that carriers a negative electric charge. It has intrinsic angular momentum of half integer of $\hbar$ (spin = ½), which means it is a *fermion*.

Hence if more than one electron occupies the same space, the properties of each electron (fermion) must be different and they obey Fermi-Dirac statistics.

This strong interaction between ferimons is described by the Pauli exclusion principle).

This gives us the Periodic Table of elements.



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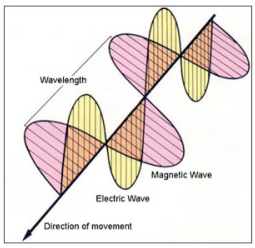
What is a photon?

A photon is an *elementary* particle of electromagnetic radiation with coupled electric and magnetic fields as governed by Maxwell's equations.

It has intrinsic angular momentum of integer value of $\hbar$ (spin = 1), which means it is a *boson*.

Hence photons do not interact with other photons, and so more than one photon can occupy the same quantum state.

Bosons satisfy the Bose-Einstein statistics.



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Electrons & photons: comparison

Moving electrons (dipole) create electric fields —> creation of light

Electric fields cause electrons to move —> detection of light

Both elementary particles exhibit both particle and wave-like behavior:

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m} \qquad \lambda = \frac{h}{\sqrt{2mE}}$$

	Electrons	Photons
Wavelength	$\lambda = \frac{h}{p} = \frac{h}{mv}$	$\lambda = \frac{h}{p} = \frac{c}{\nu}$
Interaction in a medium	Coulomb interaction	Dielectric constant (refractive index)

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Comparison (cont.)

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

	Electrons	Photons
Eigenvalue (wave) Equation	$-\frac{\hbar^2}{2m}\nabla^2\psi + V(r)\psi = E\psi$	$\nabla^2 \boldsymbol{E} - \varepsilon\left(\frac{\omega}{c}\right)^2 \boldsymbol{E} = 0$
Free space propagation (plane wave)	$\psi = \text{const}\left(e^{ik\cdot r - \omega t} + e^{-ik\cdot r + \omega t}\right)$	$\boldsymbol{E} = \frac{1}{2}E_0\left(e^{ik\cdot r - \omega t} + e^{-ik\cdot r + \omega t}\right)$
Confinement length scale	10 eV electron: λ = 0.338 nm	1.24 eV infrared photon: λ = 1.24

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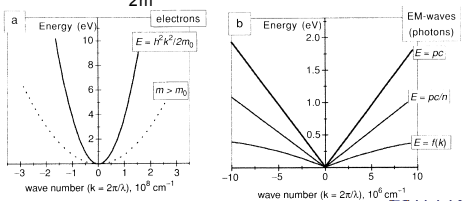
Dispersion relations

Free space propagation of both electrons and photons can be described by plane waves with wave vector k.

For electrons $k = \frac{mv}{\hbar}$ while for photons $k = \frac{2\pi}{\lambda}$

For electrons $E = \frac{\hbar^2 k^2}{2m}$ while for photons $E = \hbar kc$



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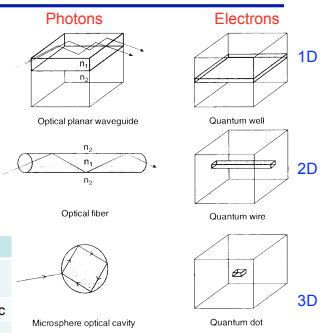
Confinement

Propagation of electrons and photons can be confined or trapped:



Confinement via various means:

electrons	photons
Coulomb force	Total internal reflection
Periodic potential	Periodic dielectric
metallic	metallic

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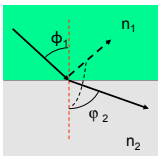
Total internal reflection

Snell's Law of refraction

$n_1 \sin \varphi_1 = n_2 \sin \varphi_2$



if $n_1 > n_2$ then φ_2 can exceed 90°

the critical angle is

$$\varphi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Light is confined within the high index region by total internal reflection

Total internal reflection occurs when angle of incidence exceeds critical angle.

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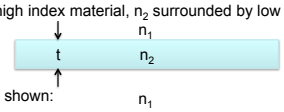
1D dielectric optical confinement

1D symmetric planar waveguide: high index material, n_2 surrounded by low index, n_1.



For optical waveguiding, it can be shown:

$$\Delta n = (n_2 - n_1) > \frac{m_s^2 \lambda_0^2}{4\, t\, (n_2 + n_1)} \qquad m_s = 0, 1, 2, 3, \ldots$$

t is the thickness of the membrane and the optical modes given by m_s.

Note that the lowest order mode, m_s=0, does not exhibit a cutoff; hence any wavelength will be supported by any thickness of membrane!

However, for decreasing thickness or small Δn, the confinement would be poor, with relatively large evanescent tails of the mode extending outside of the membrane.

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Electronic quantum confinement

Quantum-confined structures are constrained to less than the de Broglie wavelength in 1, 2, or 3 dimensions.

Under these conditions, the energy is increased and or the wavelength is shortened.

Example

Thermal energy: $\frac{mv^2}{2} = kT$ corresponding de Broglie wavelength: $\lambda = \frac{h}{\sqrt{2mkT}}$

For T = 300 K, the deB λ in GaAs is approximately 30 nm for electrons and 11 nm for holes

To achieve quantum-confinement, one or more dimensions must be less than 10 nm.

Artificial structures with quantum-confinement in 1, 2, or 3 dimensions are:

quantum wells,

quantum wires, and

quantum dots, respectively.

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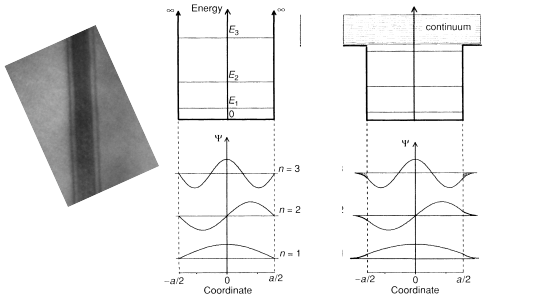
1D electronic confinement (quantum wells)

Example: 1D potential well surrounded by infinite and finite barriers



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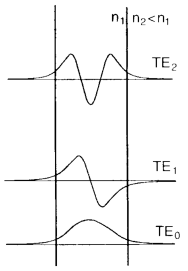
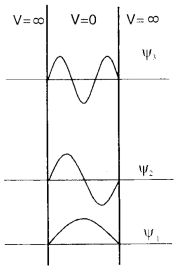
1D confined modes

For various degrees of confinement, can solve Helmholtz/Schrodinger equation to find confined modes (wavefunctions):

TE photon mode in planar waveguide



Electron wavefunction in



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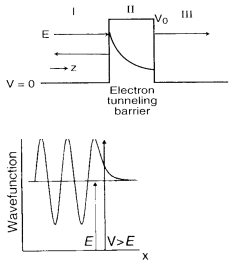
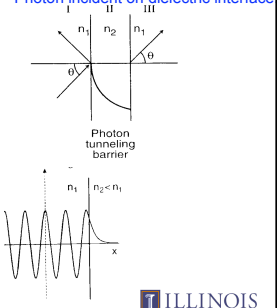
1D Tunneling

Both photon & electron can "leak" out of confinement potentials:

Electron impinging on finite barrier:



Photon incident on dielectric interface



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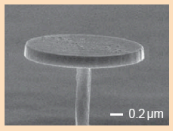
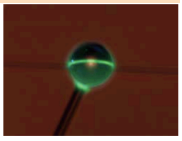
2D Optical confinement: whispering gallery

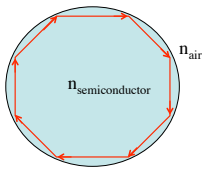
Use total internal reflection to trap light within circular/spherical cavity

Disk





Silica WGR doped with Er



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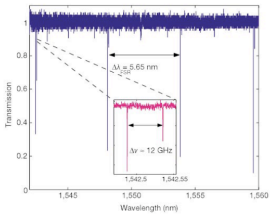
Whispering gallery cavities

Ultra-high-*Q* toroid microcavity on a chip

D. K. Armani, T. J. Kippenberg, S. M. Spillane & K. J. Vahala

Nature **42**, 926 (2003)



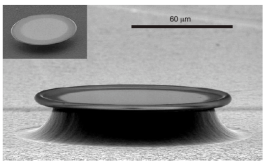


Figure 2 Scanning electron micrograph of a silica microdisk after selective reflow treatment with a CO_2 laser. The inset shows the microdisk prior to laser treatment. This toroidal microresonator had an intrinsic cavity *Q* of 1.00×10^8.

Formation of silica waveguides on Si, where the edges of disk are ultra-smooth, producing very low loss.

Coating the outside of disk with "stuff" enables sensing of very small changes of refractive index.

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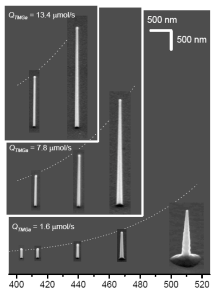
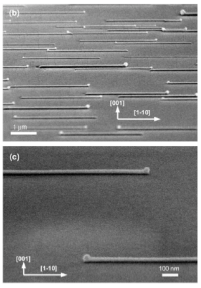
2D electronic confinement: nanowires



Vertical nanowire growth rate is temperature activated



Lateral nanowire growth also depends on growth temperature

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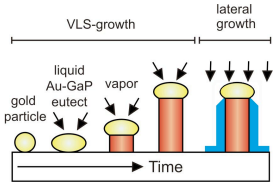
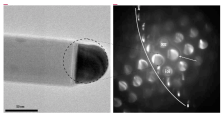
Semiconductor nanowire growth

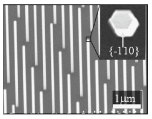
Vapor-liquid-solid (VLS)
Si whiskers grown from Au catalysts
Broadly adapted for other materials



Vapor-solid-solid (VSS)
GaAs NW growth from Au catalysts
TEM imaging showed single crystal tips



Persson, et.al. 2004.



Catalyst-free NW growth
SA-MOVPE (GaAs NW on GaAs & Si)
Vapor-Solid Growth (oxides – ZnO NWs)
Oxide-Assisted Growth (GaAs NWs)
Organic assisted Growth (InAs NWs on Si)

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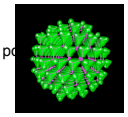
3D optical confinement: colloidal dots

Colloidal semiconductor nanocrystals are pieces of semiconductor so small that the electronic properties depend on crystal size. Quantum confinement leads to variation of the bandgap (and therefore absorption) of the nanocrystal depends on its diameter.

Growth by chemistry – particles that are 1-100nm diameter



Control: size, shape, composition (metals, semiconductors, po layers. etc.)

Synthesis – chemical reaction by pre-cursors in solvent
- form nuclei, grow crystallites
- cap surface with surfactant (long chain molecule)
- functionalize outer surface

Size Dependence of Optical Properties
In general, confinement produces a blue shift of the band-gap.

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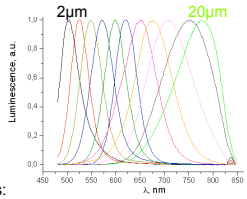
Examples of colloidal dots

CdSe quantum dots of different sizes.

CdTe quantum dots of different sizes.



Effects of colloidal dot heterostructures:

	Composition	Photoluminesence	diameter
Green	CdSe/ZnS	517nm	25nm
Yellow	CdSe/ZnS	567nm	28nm
Orange	CdSe/CdS/ZnS	589nm	22nm
Red	CdSe/CdS/ZnS	610nm	21nm
Blue	CdS/ZnS	420nm	4nm

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Self assembled quantum dots

Semiconductor quantum dots: electronic confinement of both the electron and hole in all three dimensions, produces electronic states that are “atomic-like”.

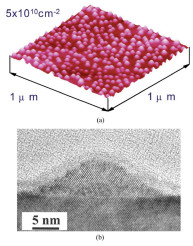
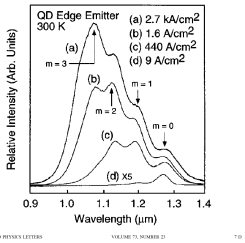


Fig. 1. (a) Atomic force microscopy image of an InAs quantum-dot layer on GaAs. (b) Cross-sectional transmission spectroscopy image of a single quantum dot grown on GaAs.



APPLIED PHYSICS LETTERS VOLUME 73, NUMBER 23 7 D

Lasing from InGaAs/GaAs quantum dots with extended wavelength and well-defined harmonic-oscillator energy levels

G. Park, O. B. Shchekin, D. L. Huffaker, and D. G. Deppe
Microelectronics Research Center, Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas 78712-1084

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   - A. Dielectric
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   - C. Metallatic
3. Metamaterials
4. Summary

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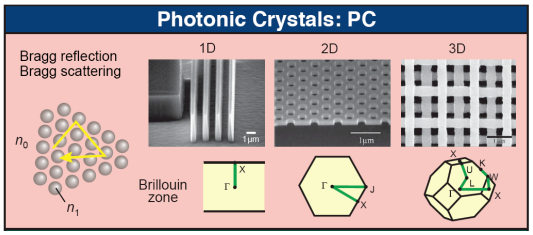
Periodic dielectric confinement



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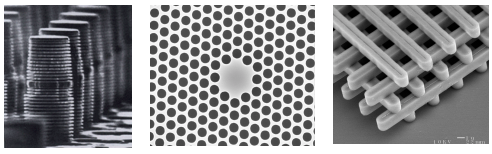
Photonic crysals

Photonic Crystal: material with periodic refractive index variation



1D 2D 3D

Photonic crystal produces a photonic band gap to act as a mirror

A defect in photonic crystal structure creates an optical cavity

Active layer in the defect provides optical gain

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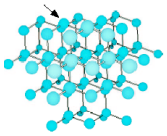
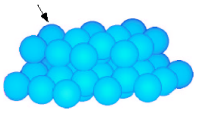
Electronic versus photonic bandgap

Periodic Medium

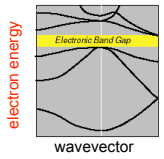
atoms in diamond structure

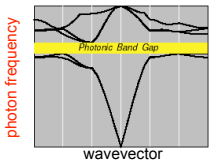


dielectric spheres in diamond lattice



Band Diagram





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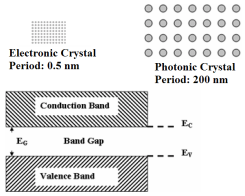
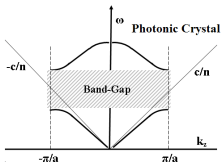
Photonic Crystals

In a periodic medium, electrons and photons can have a *bandgap* in their allowed energy spectrum



Electronic Crystal

Solution of Schroedinger's equation in periodic coulomb potential forbids electrons with energies within the Energy Band-Gap.



Propagation of light within periodic refractive index (photonic crystal) is forbidden for a range of frequencies resulting in photonic bandgap.

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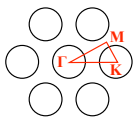
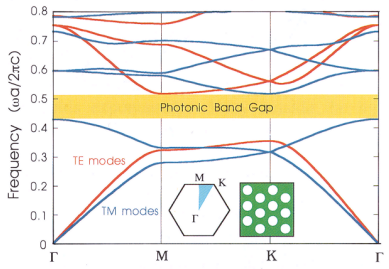
2D pattern of air holes

Hexagonal lattice of air holes in semiconductor has overlapping photonic bandgap for both polarizations; this is the most common photonic crystal.

Real Space





Photonic Crystals, J. Joannopoulos, R. Meade, J. Winn (Princeton Press 1995)

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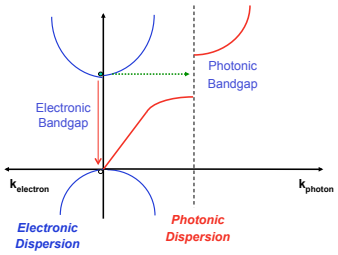
Combine electonic & photonic confinement



$k_{electron}/1000 \approx k_{photon}$

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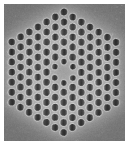
Photonic crystal defect cavity lasers

First demonstration by CalTech & USC team: Science **284** (1999)

Lasers shown below fabricated at the University of Illinois



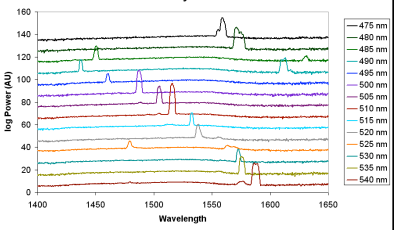


Photo-pumped with 980 nm diode laser

r/a = 0.33 r'/a = .24

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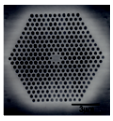
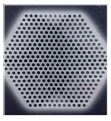
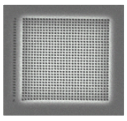
Examples of Photonic Crystal Lasers

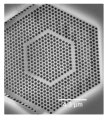
Y. H. Lee, et al. KAIST

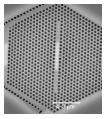

Triangular Lattice
Defect Laser

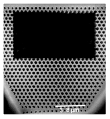
Square Lattice
Defect Laser


Triangular Lattice
Band-Edge Laser


Square Lattice
Band-Edge Laser


Hexagonal ring Laser


Stick Laser


Surface Mode Laser

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Nanophotonics Outline

1. Light/matter interaction
2. Confinement
   - A. Dielectric
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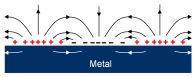
Plasmonics

Plasmon: collective longitudinal excitation of conduction electrons in metals, which couple into electromagnetic radiation; allows propagation of light above the plasma frequency in metals!



Collective excitation of "free" electrons on **metal** surface

Surface plasmon-polariton: E&M wave + electrons at dielectric/metal interface; propagates along interface; evanescently decaying in transverse directions;

Metallic nanostructure: use metal to guide/store photon

Advantages – compress mode size
strong coupling between photon and material

Disadvantages – large optical absorption
fidelity of nanostructures

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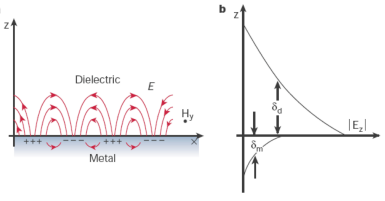
Plasmonics (cont)

Dielectric $z > 0$

$$E_z^d = E_o^d e^{ik_z^d z} e^{ik_{sp}x}$$

Metal $z < 0$

$$E_z^m = E_o^m e^{-ik_z^m z} e^{ik_{sp}x}$$



EM waves propagating along interface with ε of opposite sign.

Intensity maximum at interface; exponentially decays away from interface.

$$k_{sp} = \frac{2\pi}{\lambda_o}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}$$

Note $\varepsilon_m \simeq -\varepsilon_d$ so effective λ very small

Optical frequencies, but x-ray wavelength

Also $n_{eff} = \lambda_o / \lambda \gg 1$

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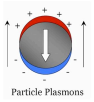
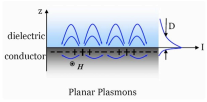
What can you do with plasmonics?

Applications of metal/dielectric surface plasmon–polariton (SPP):

1) Metal apertures (anomalous transmission, tunable arrays)
2) Light waveguiding and switches (very short λ)
3) Light confinement in cavities (enormous n_{eff})
4) Metal nano-particles and metal nano-shells
5) Electric field enhancement: biological sensing–SERS
   nonlinear optics
6) Below diffraction limit imaging
7) Fabricate beautiful glass vases and stained glass windows!


Particle Plasmons



Planar Plasmons

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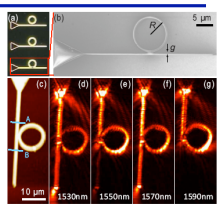
Plasmonic waveguides

Thin Au strips on glass to form optical waveguides.

Light shines onto the "funnel" structure to excite plasmon, which propagates down waveguide. At the end, E&M radiation is emitted.

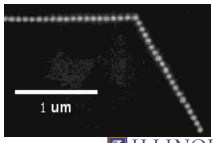
APL 94, 051111 (2009)



Array of 5 nm diameter Au particles

Waveguiding at wavelength less than diffraction limit!

Optical waveguides for nanoscale devices?



Phys Rev. B **64**, R16356 (2000); Adv. Mat. **13**, 1501 (2001)

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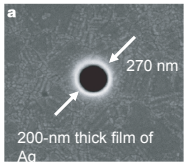
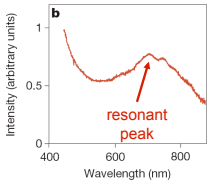
Transmission through metal nanoaperture



Single hole in Ag film



Transmission spectrum

Localized surface plasmons (SPs)

Excitation of SP modes at the edges of the hole

SP resonances result in transmission peaks for certain wavelengths

C. Genet and T. W. Ebbesen, "Light in tiny holes", *Nature*, vol. 25, 2007

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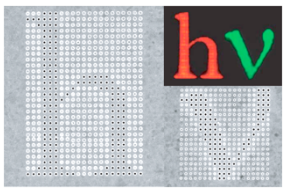
Transmission through periodic nanoapertures

Holes in a dimple array



Array of dimples prepared by FIB milling in Ag film

When illuminated with white light, transmitted colour is determined by period of array

Period of 550nm for red

Period of 450nm for green

C. Genet and T. W. Ebbesen, "Light in tiny holes", *Nature*, vol. 25, 2007

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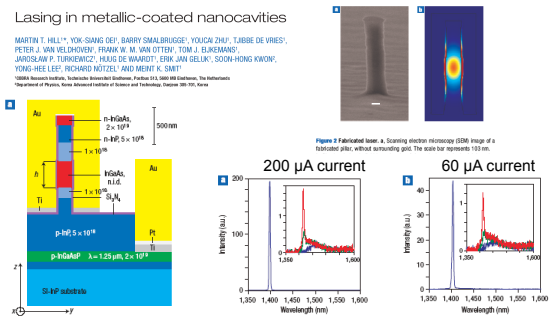
Metal confined nanolaser diode

Lasing in metallic-coated nanocavities



Nature Photonics 1, 589 (2007)

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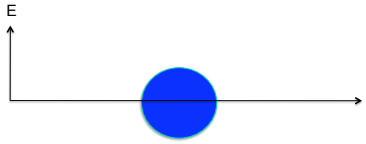
Metal nano-particles

For metal nanoparticles, surface plasmon is confined within a small volume; we call this localized surface plasmon

Assume particle size << absorbing light wavelength

As the field goes by, it will oscillate the electron cloud around the metal nanoparticle



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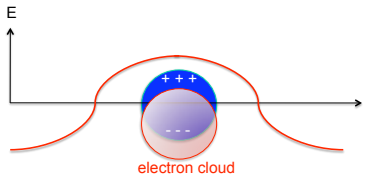

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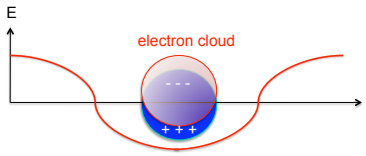

The oscillation of negative electron cloud relative to the positive ion charge creates a surface plasmon

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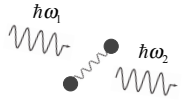
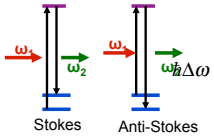
Surface enhanced Raman scattering (SERS)

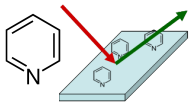
Raman scattering from interactions of photons and molecular states:



$\omega_2 - \omega_1 = \pm\Delta\omega$



SERS



Field enhancement due to surface plasmon resonance can be as high as $|\mathbf{E}|/|\mathbf{E}_0| \sim 10^3$

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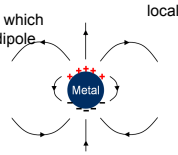
SERS (cont.)

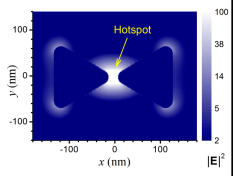
Can deposit metal nanoparticles or metal patterns to locally enhance electric fields which lead to dramatic enhancement of Raman scattering.

Raman enhancement can be as much as 10^5 for single particles and 10^{11} for particle aggregates. Any material can be used but enhancements are maximized for Ag, Au, and the alkali metals.

Nanosphere has resonant plasmon, which induces dipole field



Bowtie also enables huge local field



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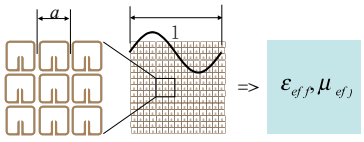
Metamaterials

- Engineered materials tailored for electro-magnetic properties not found in nature
- Artificially designed materials with subwavelength structuring
  - Can exhibit **special ε_{eff} and μ_{eff}** not available in nature
  - Physical origin: local resonances induced by microstructure
  - Working frequency range is usually quite narrow.



Microstructures with local resonances | Homogenization | An effective medium with special ε_{eff} and μ_{eff}

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Electromagnetic waves in materials

Source-free Maxwell's equations in a medium

$$\nabla \cdot \mathbf{D} = 0$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = i\omega \mathbf{B}$$
$$\nabla \times \mathbf{H} = -i\omega \mathbf{D}$$

Constitutive relations

$$\mathbf{D} = \varepsilon_0 \varepsilon \mathbf{E}$$
$$\mathbf{B} = \mu_0 \mu \mathbf{H}$$

ε_0 Electric permittivity in vacuum

μ_0 Magnetic permeability in vacuum

Material properties are described in

ε and μ

Relative permittivity and permeability

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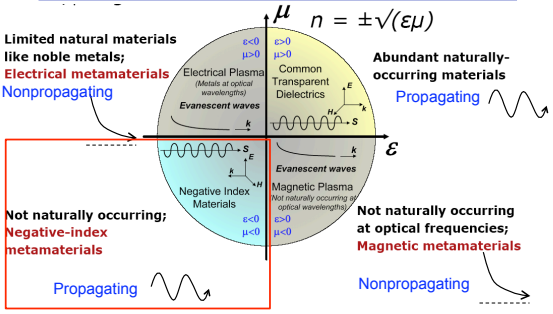
Relative permittivity & relative permeability



"Double negative materials"

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Refraction for double negative materials

Note the negative group/phase velocity, and the "left-handed" refraction, yet energy propagates in expected direction!

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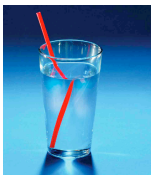
"Double negative" images

Picture a straw in a glass half-filled with water. A positive refractive index produces the expected diffraction (left).

Now imagine the liquid in the glass has negative refractive index ($n_{liquid} = -1.3$).
Now the straw is shifted "the wrong way" (right).

$n_{liquid} = 1.3$



$n_{liquid} = -1.3$

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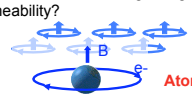
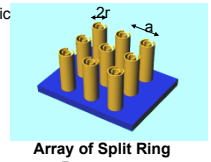
Negative magnetic permitivity metamaterials

Metals naturally have negative dielectric constant; so how do we get negative magnetic permeability?

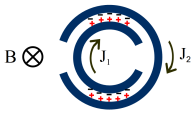


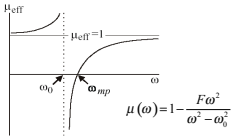
Atom

Magnetism in natural materials fades away above 100 GHz



Array of Split Ring Resonators





$$\mu(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2}$$

Can obtain a ***resonance*** frequency with μ < 0

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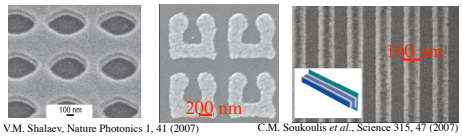
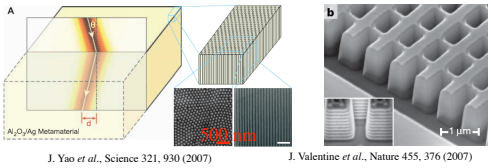
Optical metamaterials



V.M. Shalaev, Nature Photonics 1, 41 (2007)

C.M. Soukoulis *et al.*, Science 315, 47 (2007)



J. Yao *et al.*, Science 321, 930 (2007)

J. Valentine *et al.*, Nature 455, 376 (2007)

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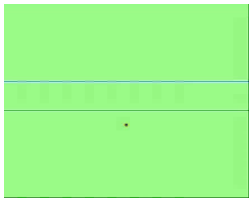
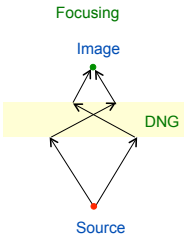
Metamaterial application: superlense

Convention lense can only focus propagating waves where $k_{||} < \omega/c$
Hence the lense is diffraction limited: resolution ≈ λ/4
Metamaterial lense also utilizes the evanescent waves, leading to better resolution





http://www.youtube.com/user/walekooen

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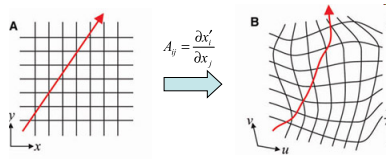
Coordinate transformation invarience

Maxwell's equations can be invarient under coordinate transformation:

Original space $\mathbf{x}$ Transformed space $\mathbf{x}'$



Original state

$$\varepsilon(\mathbf{x}), \mu(\mathbf{x}), \mathbf{E}(\mathbf{x}), \mathbf{H}(\mathbf{x})$$

$$\varepsilon'(\mathbf{x}') = \frac{\mathbf{A}\varepsilon(\mathbf{x})\mathbf{A}^{\mathrm{T}}}{\det \mathbf{A}} \qquad \mathbf{E}'(\mathbf{x}') = (\mathbf{A}^{\mathrm{T}})^{-1}\mathbf{E}(\mathbf{x})$$

$$\mu'(\mathbf{x}') = \frac{\mathbf{A}\mu(\mathbf{x})\mathbf{A}^{\mathrm{T}}}{\det \mathbf{A}} \qquad \mathbf{H}(\mathbf{x}') = (\mathbf{A}^{\mathrm{T}})^{-1}\mathbf{H}(\mathbf{x})$$

J.B. Pendry *et al.*, Science 312, 1780 (2006)

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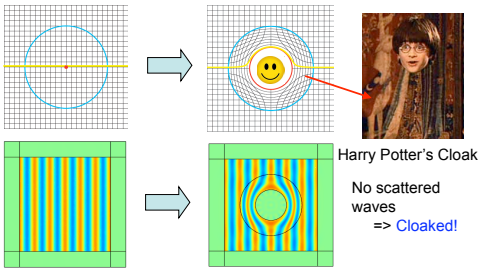
Cloaking by transformation optics



Harry Potter's Cloak

Plane wave

No scattered waves
=> Cloaked!

J.B. Pendry *et al.*, Science 312, 1780 (2006)
H. Chen *et al.* Nature Materials 9, 387 (2010)

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Summary

Nanophotonics is nanoscale interaction between light and matter

Inherently quantum mechanical phenomena, since both electrons and photons can be confined to less than wavelength

We can fundamentally change the interaction by how we confine electrons and photons

By engineering matter, we can create interactions that do not happen in nature

Lots of great research and fun!

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