Photonic crystals, PHYS-605

Ecole doctorale photonique

Romuald Houdré

Summer semester 2017

Introduction

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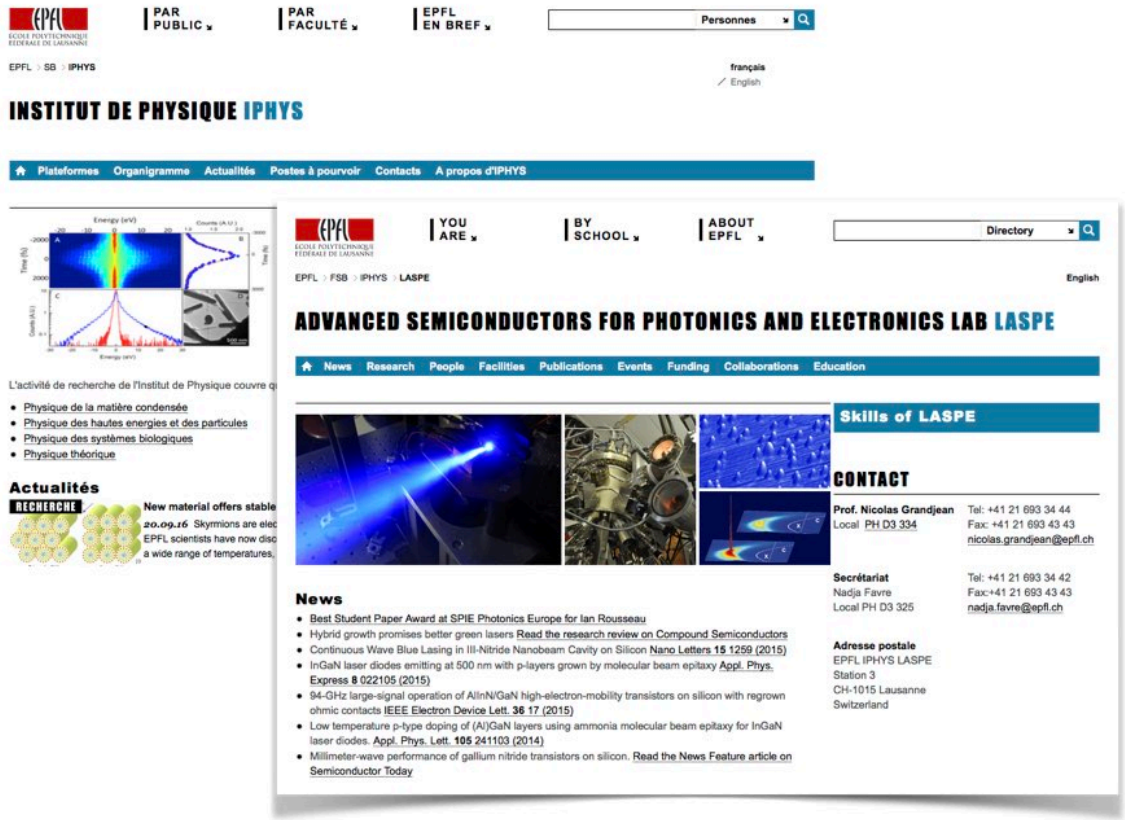


Planning

Lectures, Lab. visits, Exam

Every Wednesday 14:15 - 17:00, PH H3 31 (subject to local change)

Lab. visits, dates to be defined

Mohamed Sabry

Processing @ IPHYS & CMI

Optical measurement, date to be defined @ IPHYS

Modelling @ IPHYS

Exam

Student presentations, during the last hour of the lectures

Examination:

Presentation exploring more in depth one topic based on a selection of key papers (≈ 30 min)

for example:

Cavité optique à grand facteur de qualité / High-Q cavities
Filtres multiplexeur-démultiplexeur / Add-drop filter
Couplage / Input-Output
Maillages métalliques / Metallic wiremeshes
Métamatériaux et réfraction négative / Metamaterials and negative refraction
Modes lents / Slow light
Cristaux photoniques plasmoniques / Plasmons photonic crystals
Cristaux photoniques THz / THz photonic crystals
Techniques de modélisation / Modelling techniques
Techniques expérimentales / Optical measurements
Analogies électrons, photons / Electron and photons analogies
...

non exhaustive list

Material: a copy of the slides can be downloaded from:

http://wiki.epfl.ch/houdre

It is strongly advised to print a copy before the lectures

Bibliography:

- **Photonic crystals : physics and practical modeling** / Igor A. Sukhoivanov, Igor V. Guryev : Berlin : Springer
- **Fundamentals of photonic crystal guiding** / Maksim Skorobogatiy, Jianke Yang : Cambridge University Press
- **Photonic crystals** / C. Sibilia, Milano : Springer
- **Photonic Crystals, Theory, Applications and Fabrication** / D. W. Prather : Wiley-VCH
- **Photonic crystals : towards nanoscale photonic devices / J.-M. Lourtioz,** Berlin : Springer

  or in French: **Les cristaux photoniques ou la lumière en cage** / J.-M. Lourtioz, Paris : Hermes-Sciences
- **Photonic crystals : advances in design, fabrication, and characterization** / K. Busch, Weinheim : Wiley-VCH
- **Photonic crystals : physics, fabrication and applications** / K. Inoue, Berlin : Springer
- **Optical properties of photonic crystals** / K. Sakoda, Berlin : Springer
- **Photonic Crystals and Light Localization in the 21st Century** / ed. Costas M. Soukoulis, Dordrecht : Kluwer Academic
- **Photonic band gap materials** / ed. Costas M. Soukoulis, Dordrecht : Kluwer Academic Publishers
- **Photonic band gaps and localization** / ed. C. M. Soukoulis, New York : Plenum
- **Photonic crystals : molding the flow of light** / John D. Joannopoulos, Princeton, Princeton University Press

- **Roadmap on photonic crystals** / Susumu Noda, Dordrecht : Kluwer Academic
- **Photonic crystals : the road from theory to practice** / Steven G. Johnson, Boston : Kluwer Academic
- **Photonic crystals : nanostructures for controlling light** / M. Charlton and G. Parker, Bristol : Institute of Physics

Contents

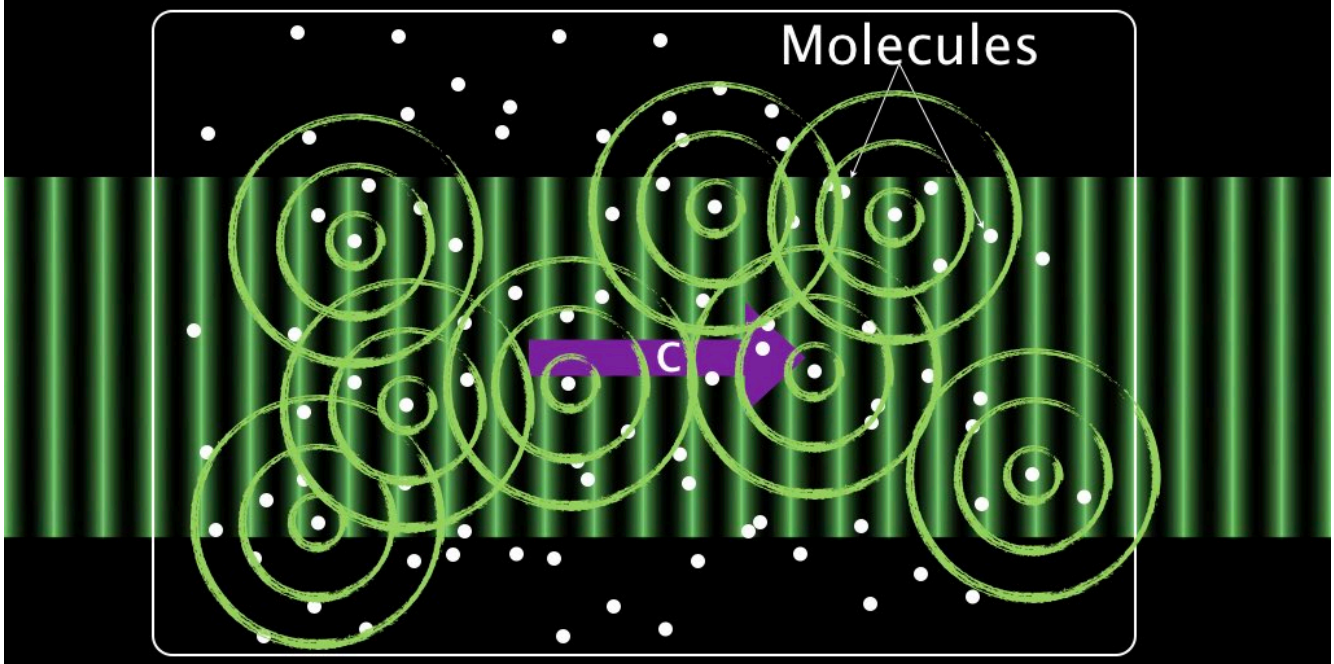
What the lecture is about :

a short introduction on photonic crystals

Three languages for one object

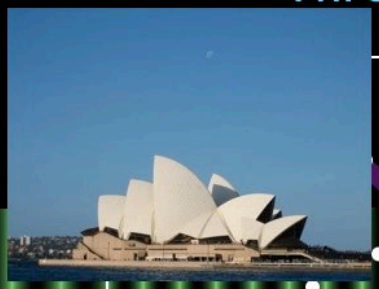
Light propagation in matter

Three languages for one object



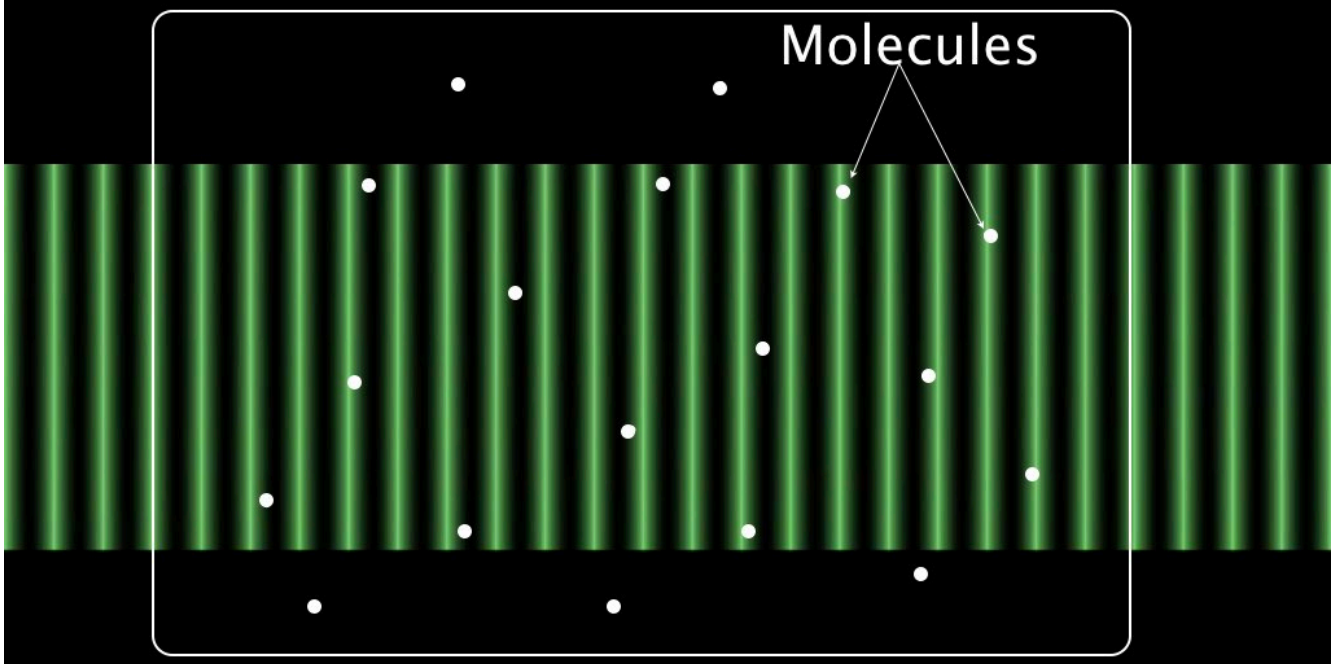
Light propagation in vacuum

Three languages for one object



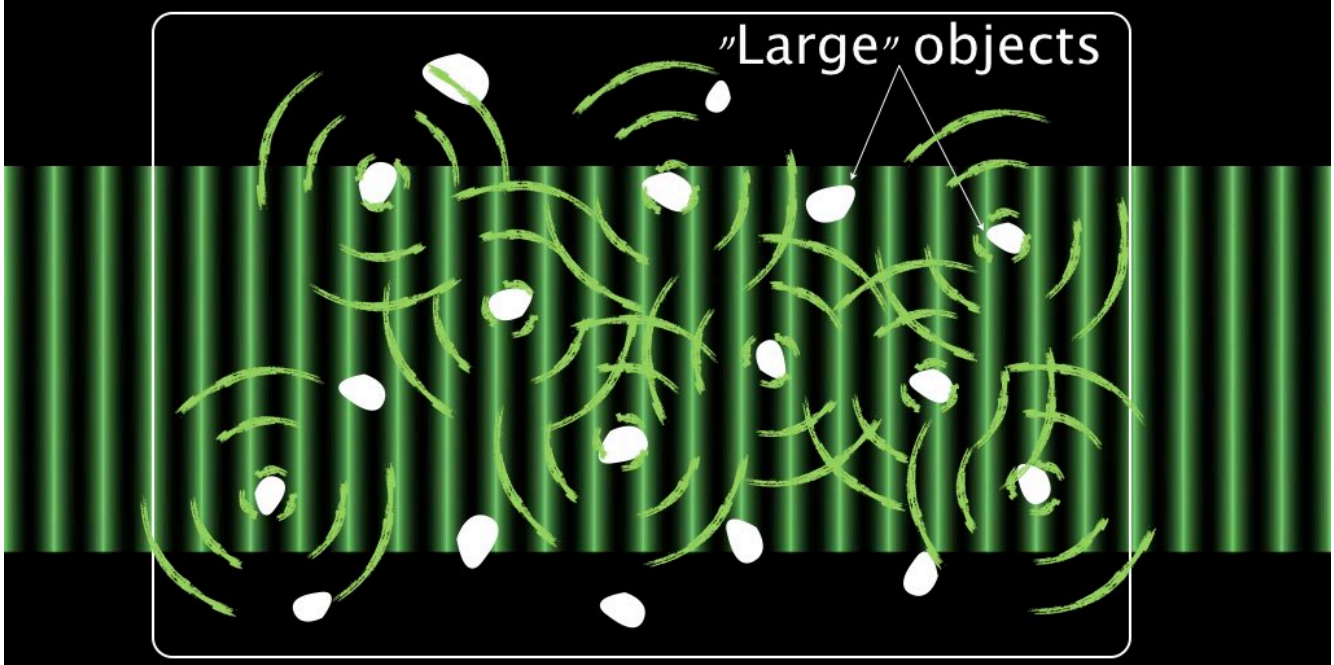
Light propagation in matter

Three languages for one object

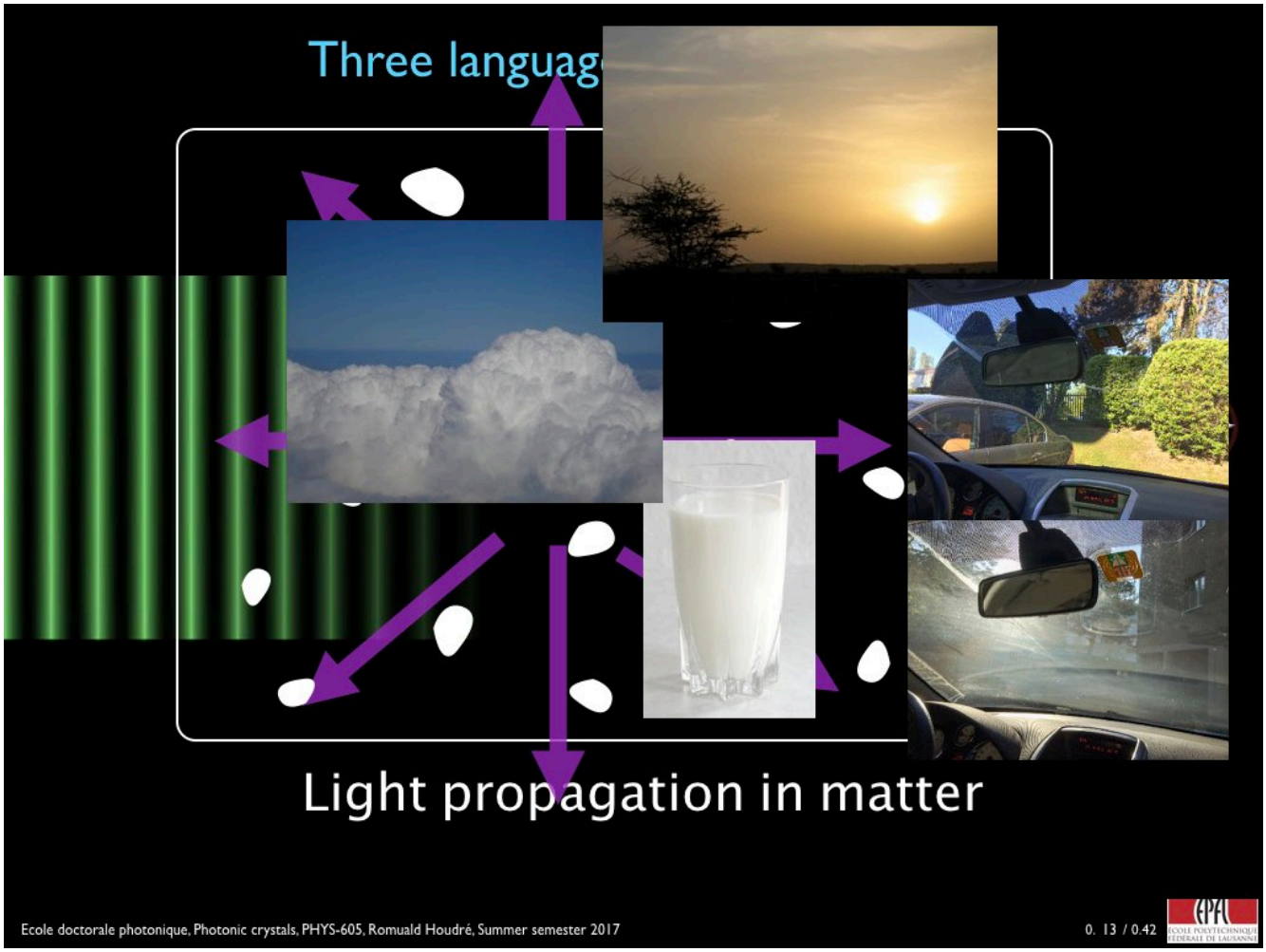


Light propagation in matter

Three languages for one object



Light propagation in matter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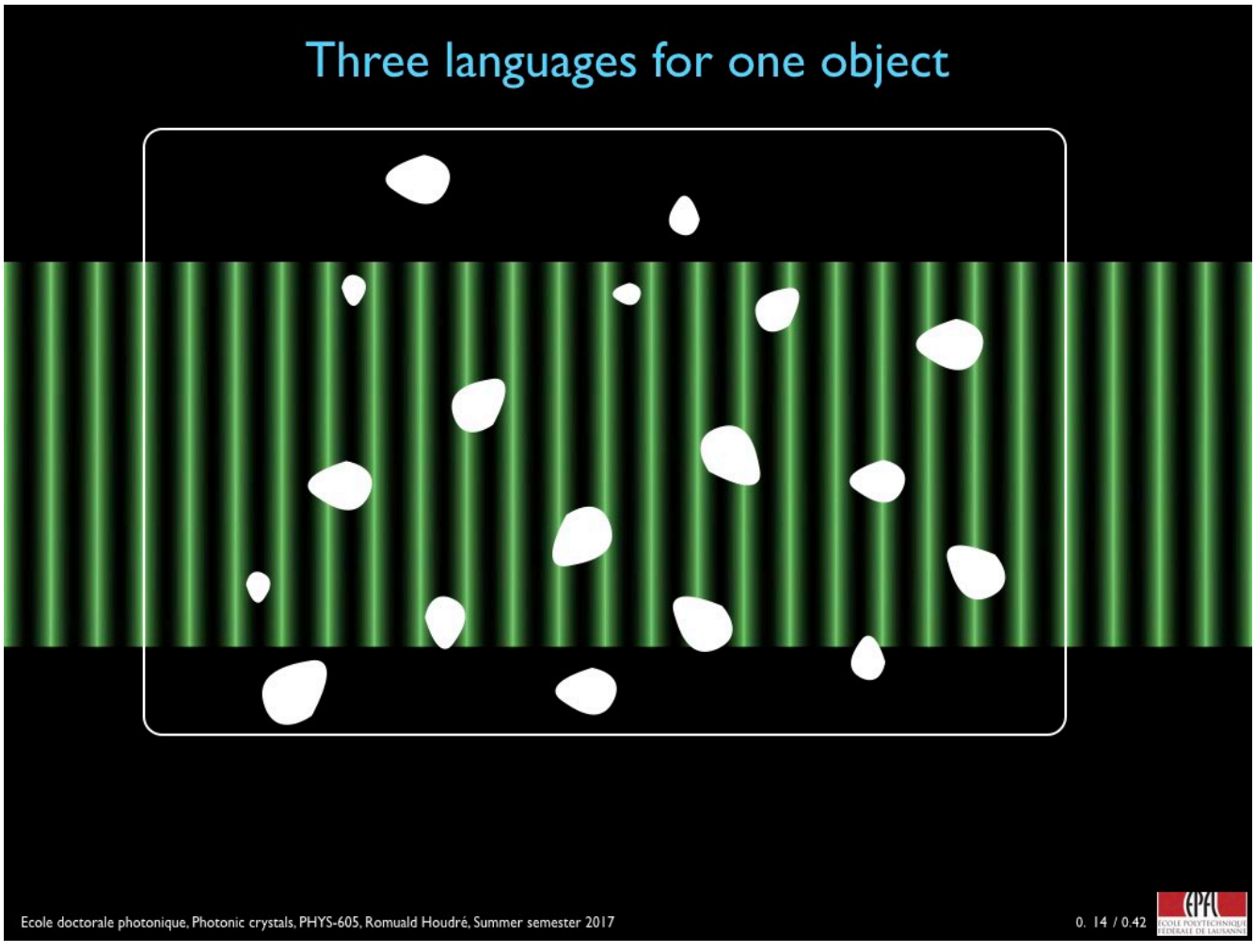
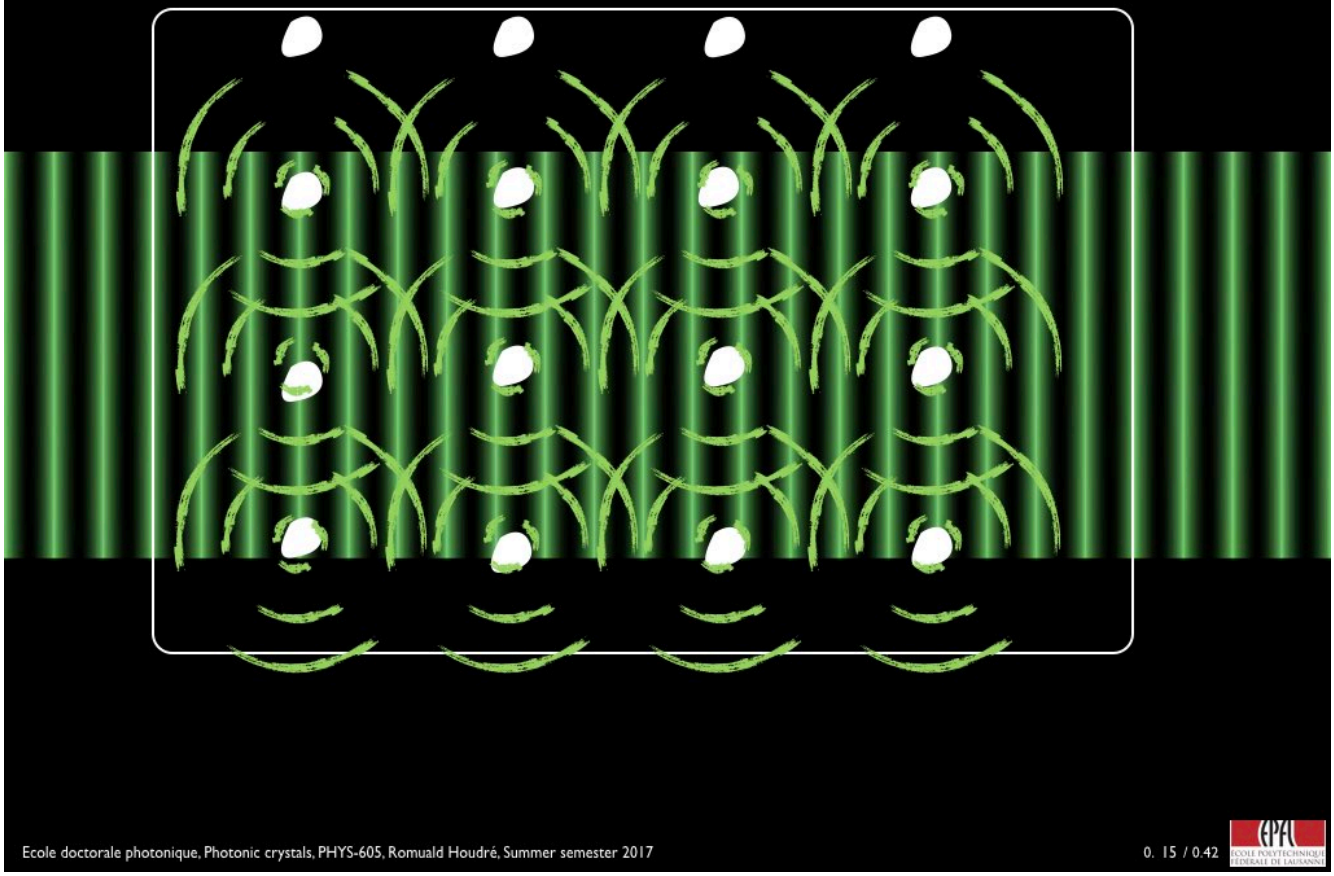
Light propagation in matter


Three languages for one object

Three languages for one object



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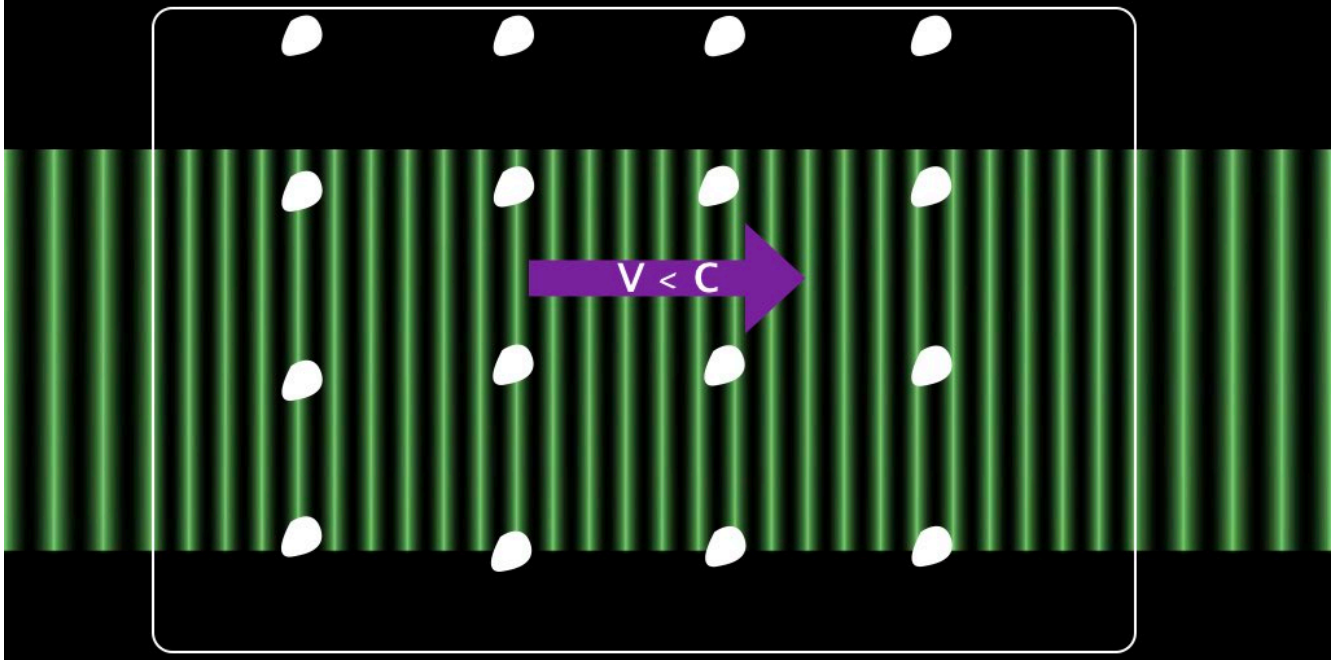

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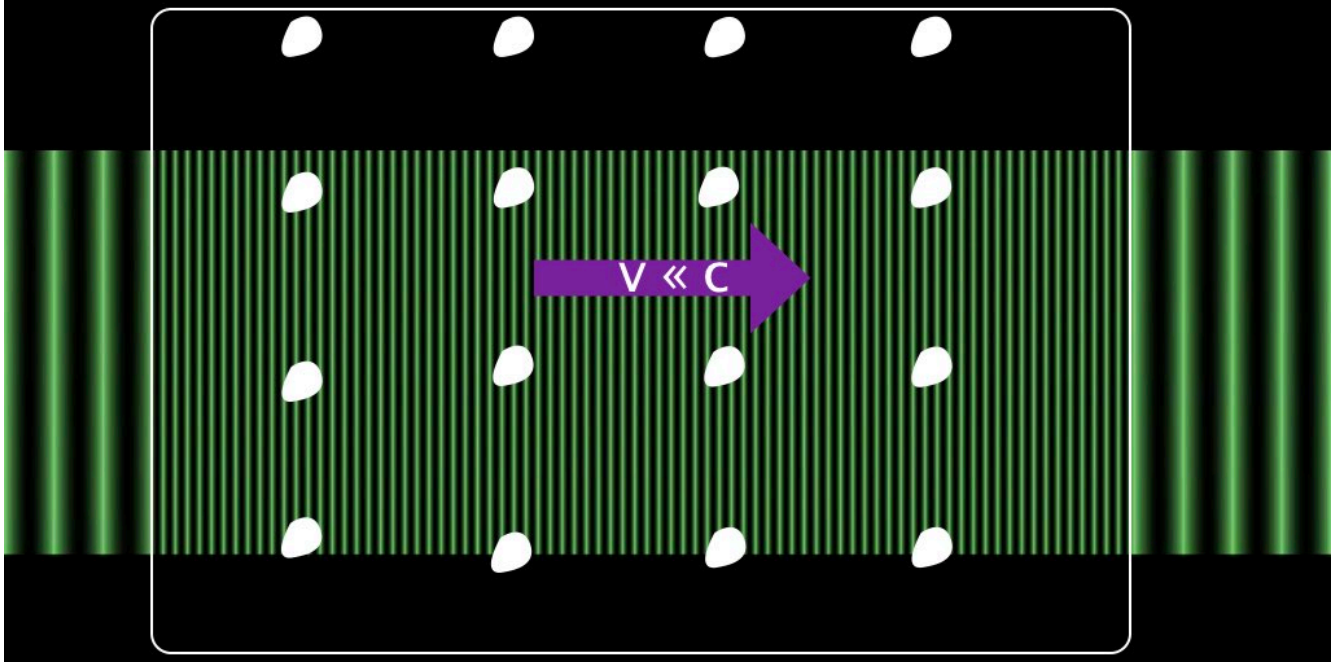
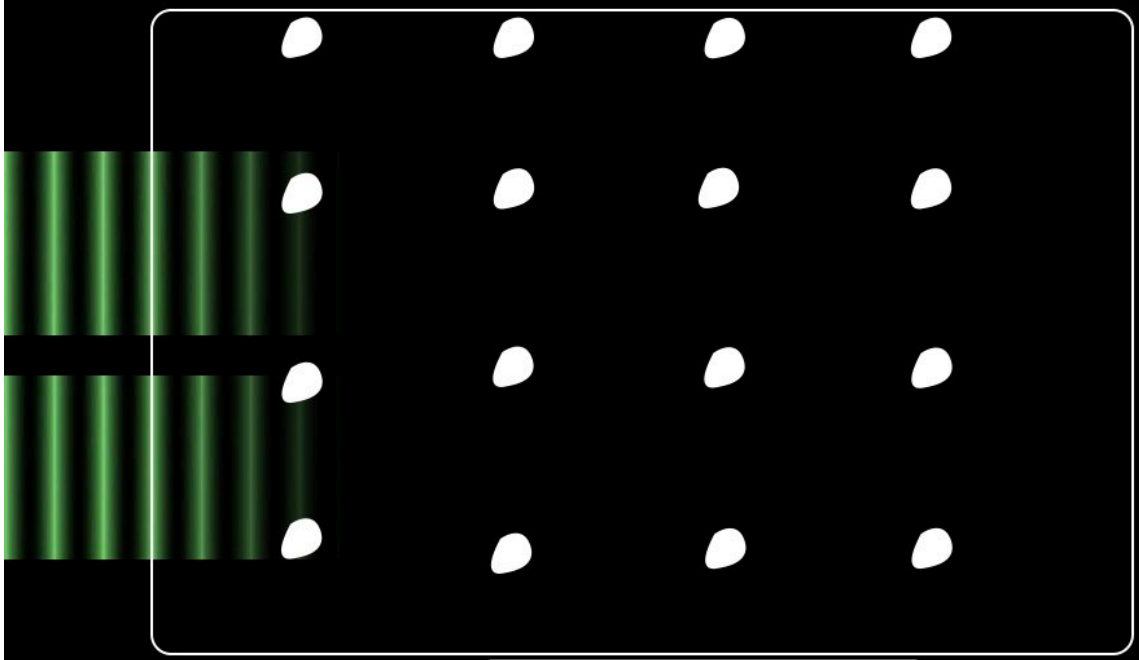


Three languages for one object



Photonic crystal

Three languages for one object

Physicist

Electrons in a crystal

↓

Crystal field, periodic potential $V(\mathbf{r})$

↓

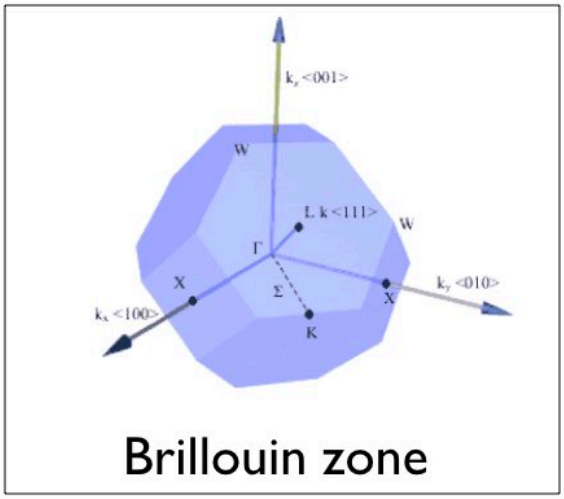
$V(\mathbf{r}+\mathbf{T}) = V(\mathbf{r})$, Bloch theorem ...

↓

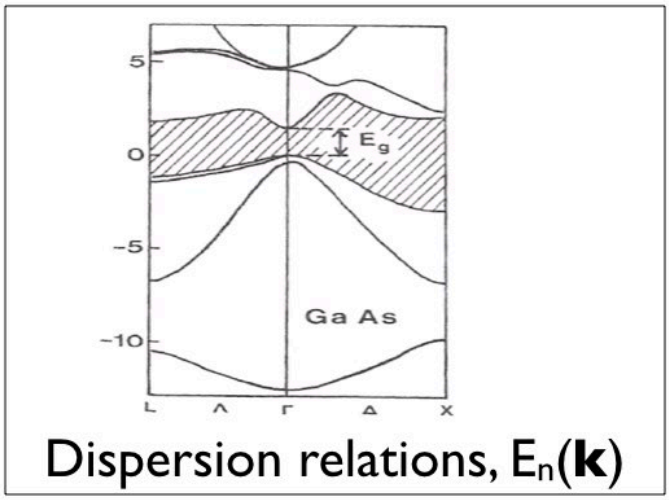
Band structure $E_n(\mathbf{k})$, n integer, $\mathbf{k}$: wave vector

Three languages for one object

Physicist



Brillouin zone



Dispersion relations, $E_n(\mathbf{k})$

✶Band of allowed states, propagation is possible

✶Band with no allowed states, propagation is impossible

Three languages for one object

Physicist

Electromagnetic wave in a periodic dielectric and loss-less medium

↓

The refractive index plays the same role for an electromagnetic wave than the crystal field for electrons

↓

Periodic refractive index n(**r**)

↓

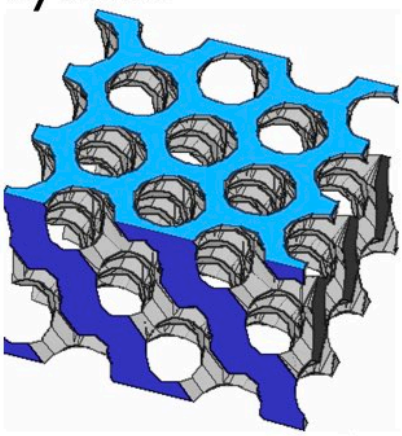
n(**r**+**T**) = n(**r**), Bloch theorem ...

↓

Band structure $\omega_n(\mathbf{k})$, n integer, **k**: wavevector

Three languages for one object

Physicist



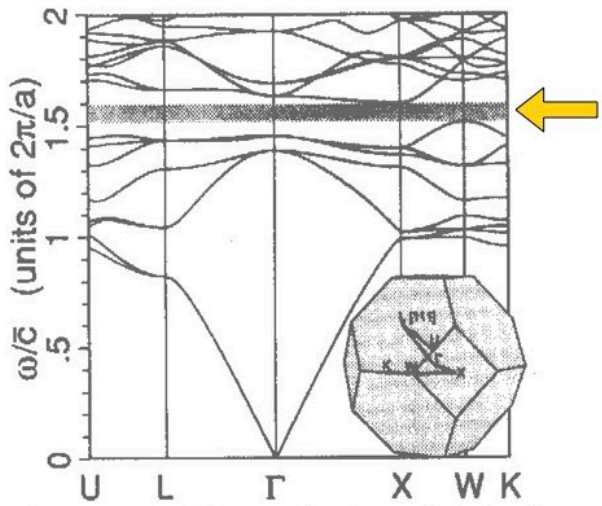


Figure 14: Band structure for EM waves for close-packed air spheres on a FCC lattice. $\bar{c} \equiv c/\sqrt{\bar{\epsilon}}$. $\epsilon_b = 13$, $\epsilon_a = 1$, $\beta = 0.74$, $\|\epsilon_r\| = 1.34$, $N = 749$. Inset shows the path in the BZ. (From Ref. [20])

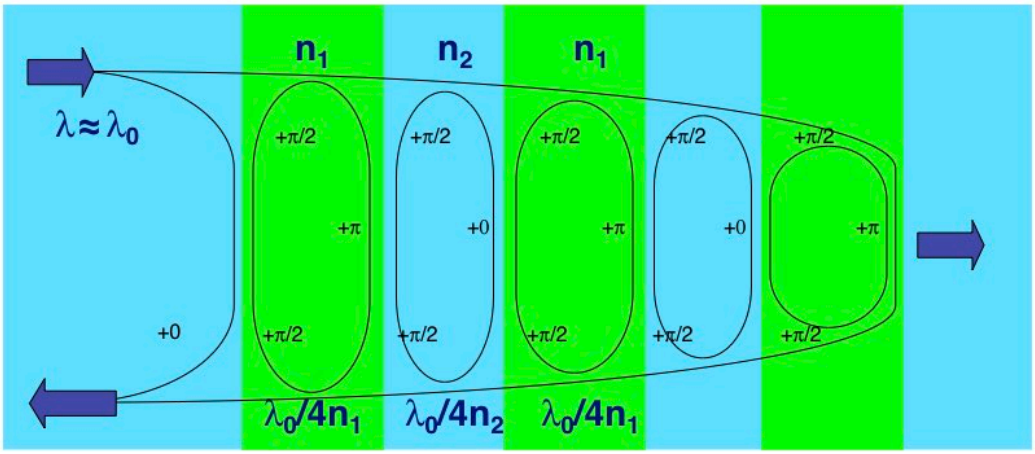
✳Band of allowed states, propagation is possible

✳Band with no allowed states, propagation is impossible

Three languages for one object

Wave optics

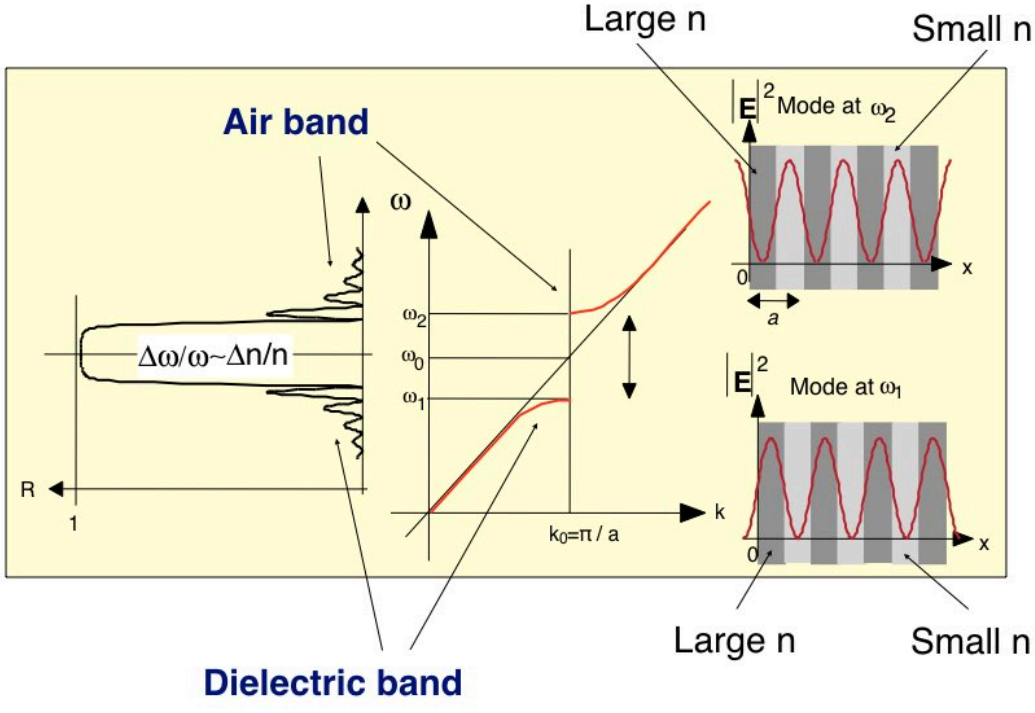
Bragg mirror: multilayers
refractive index n_1 and n_2



Reflected waves interfere constructively and lead to a large reflectivity, R ≈ 1 and T ≈ 0 at $\lambda \approx \lambda_0$

Three languages for one object

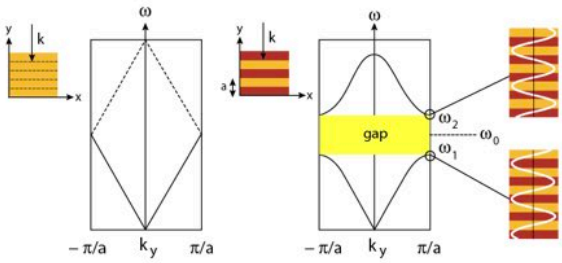
Wave optics



Three languages for one object

Wave optics bis, coupled modes

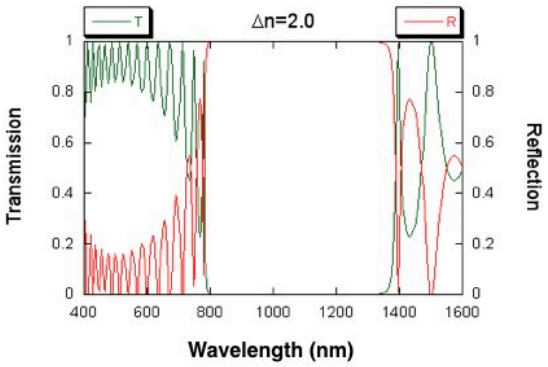
Periodic dielectric structure 1D

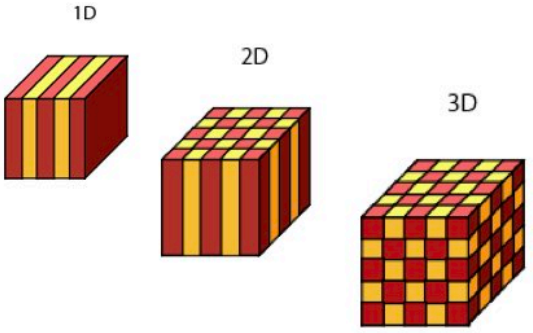


Coupled modes

Forbidden band around normal incidence

10 Bragg pairs in air (n_{high}=3.48, n_{low}=variable)

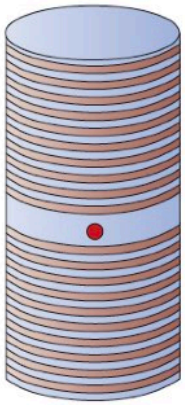




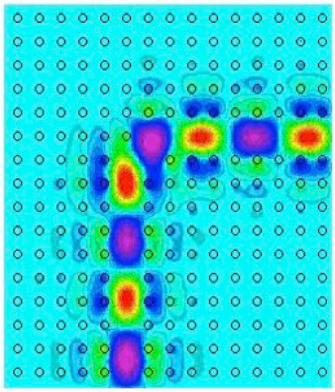
Periodic dielectric structure 3D

Forbidden band around for all incidence and propagation direction (and all polarisation)

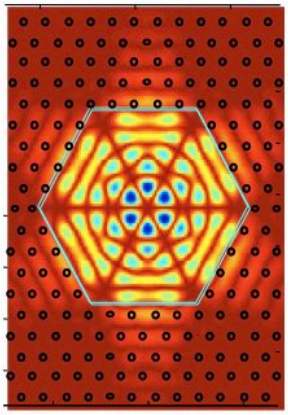
Like in semiconductors, richness of the field will come from the possibility to insert defects and impurities



Bi-dimensional defect
Planar cavity



One-dimensional defect
Wave guide



Point defect
Optical cavity

Photonic crystal zoology

Refractive index modulation

✳in 1 direction of space

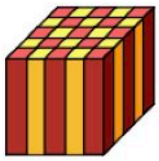
- multilayer stack of dielectrics

1D

✳in 2 directions of space

- lattices in planar waveguides
- microporous systems

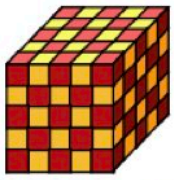
2D



✳in 3 directions of space

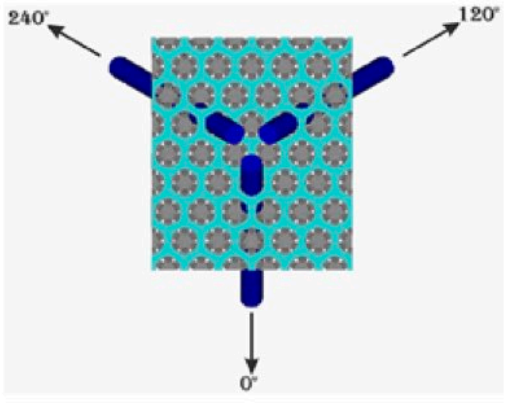
- self-organized, opals
- micro (nano-) fabrication
- microporous systems

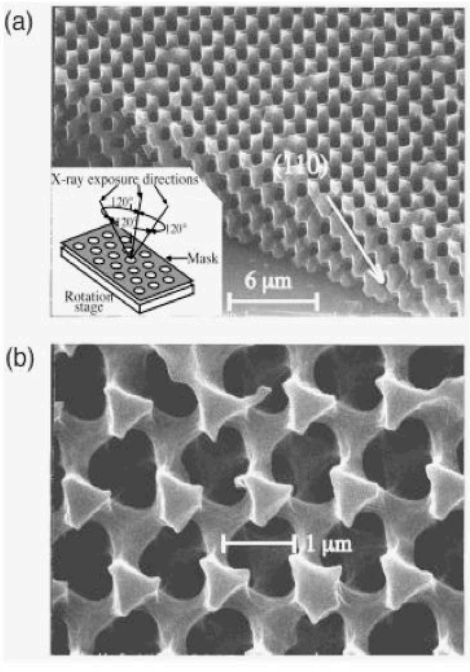
3D



Photonic crystal zoology, 3D

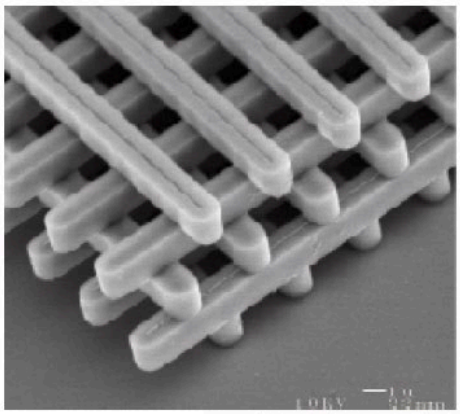
Etching (Yablonovite)

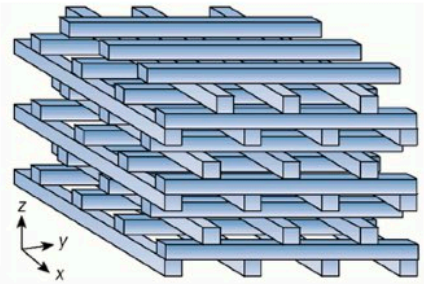




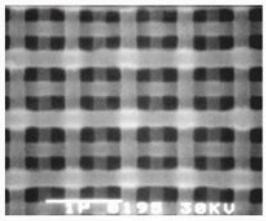
Photonic crystal zoology, 3D

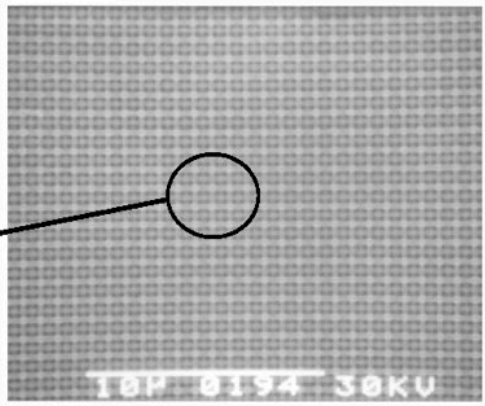
Micro-fabrication





"Wood pile"



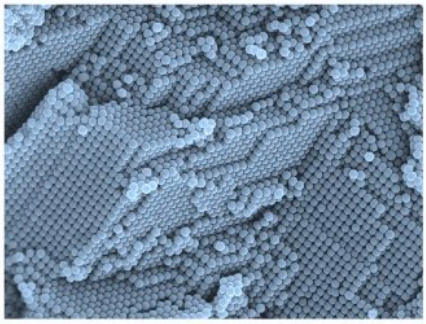


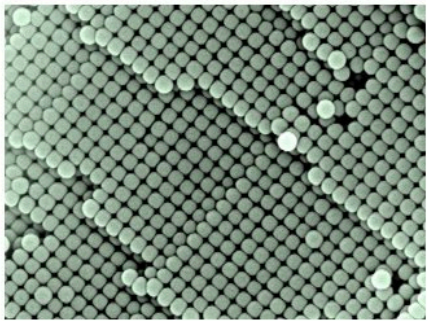
0.7µm

10µm

Photonic crystal zoology, 3D

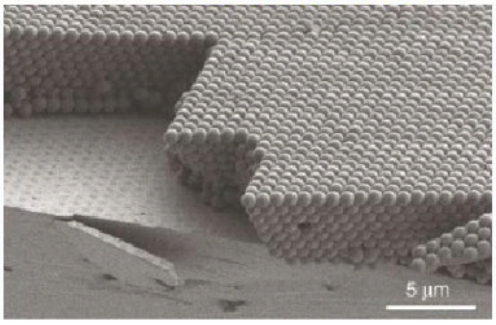
Self-organized

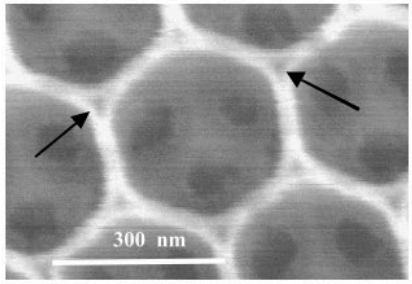




Opals

Silica or latex stacks

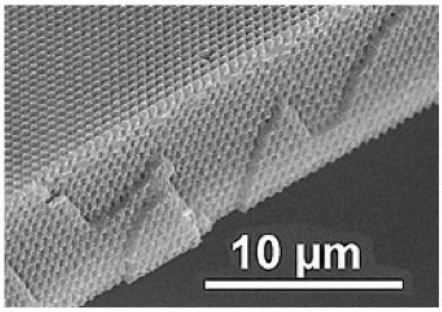


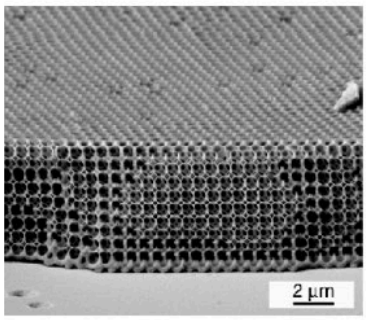


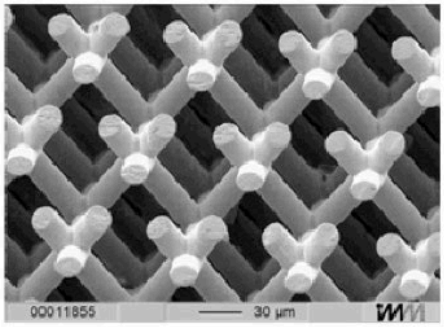
inverted structures by
infiltration and selective etching

Photonic crystal zoology, 3D

Holography

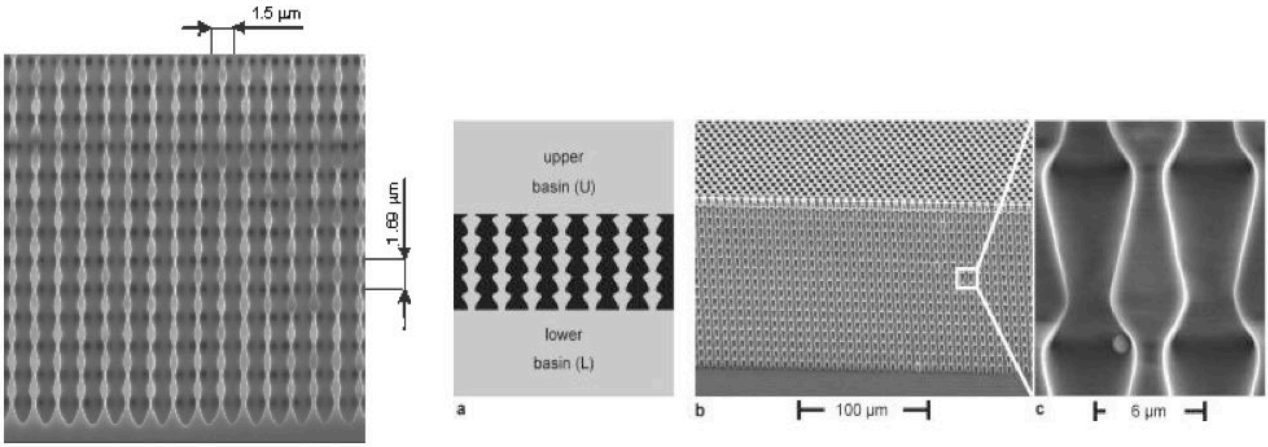






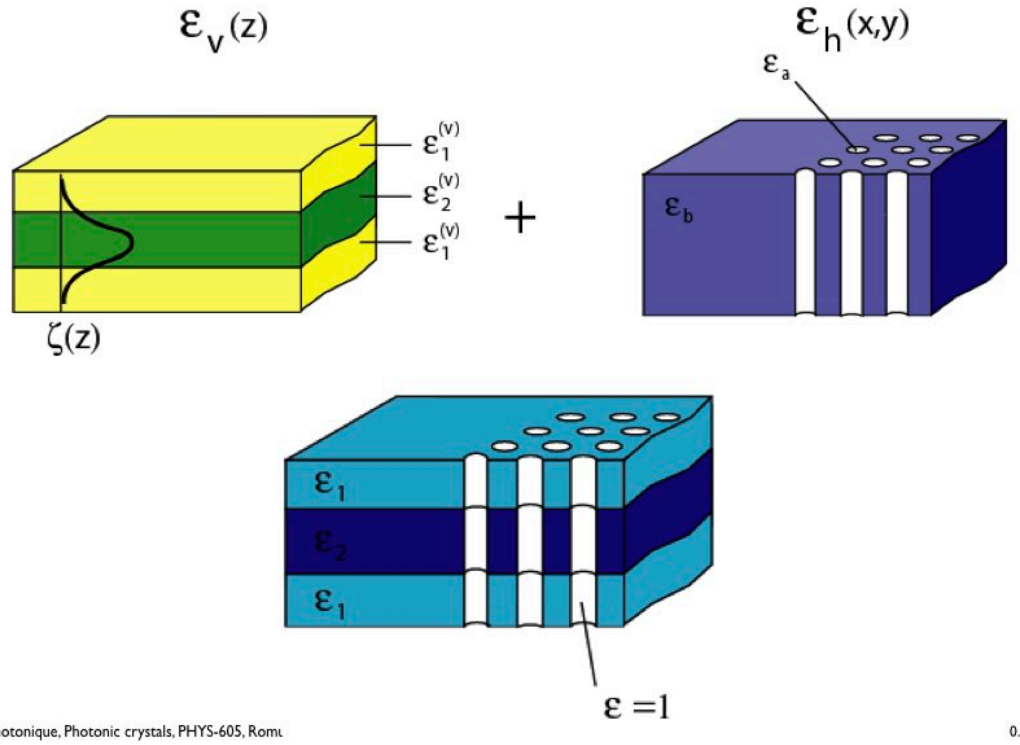
Photonic crystal zoology, 3D

Microporous silicium (anodization)



Photonic crystal zoology, 2D

2D patterning + planar waveguide

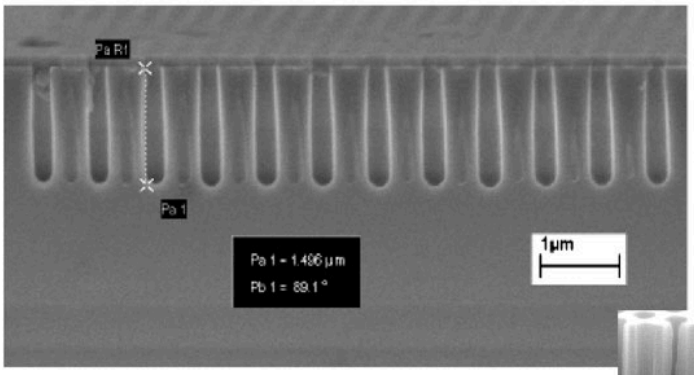


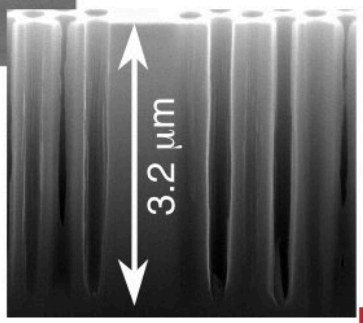
Photonic crystal zoology, 2D

2D patterning + planar waveguide

Planar waveguide, low index contrast $|n_1-n_2| << n$

"2+1" D





$InP / Ga_{1-x}As_xIn_xP_{1-x-y}$

$GaAs / Al_xGa_{1-x}As$

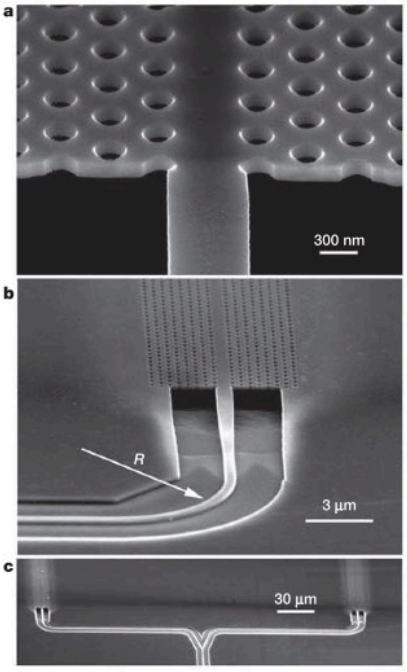
Photonic crystal zoology, 2D

2D patterning + planar waveguide

Planar waveguide, large index contrast

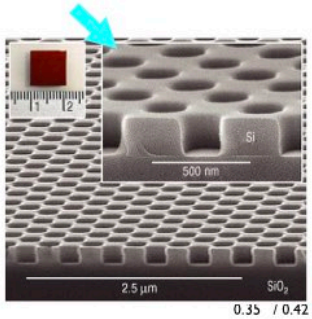
n_1-n_2 >> n

"2+1" D



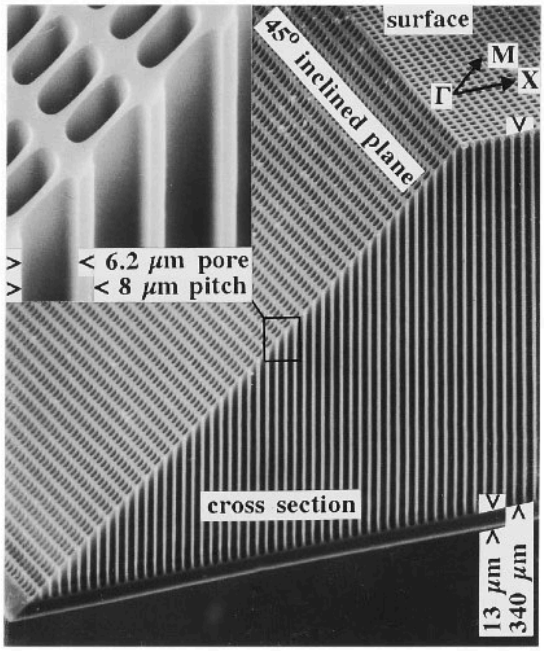
membrane
air/Si
GaAs /air
InP/air

air/Si/SiO_2
air/InP/BCB



Photonic crystal zoology, 2D

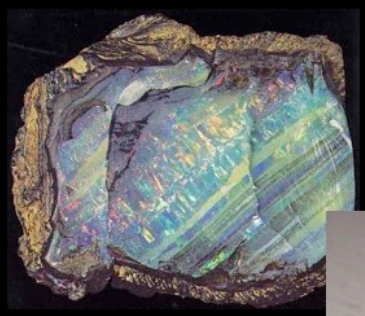
Pure 2D objects
Infinitely extended in the third dimension



Si microporous

Photonic crystal in nature

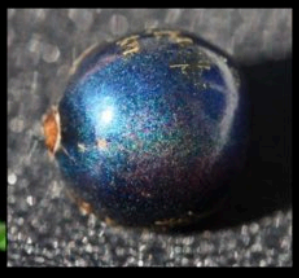
Mineral

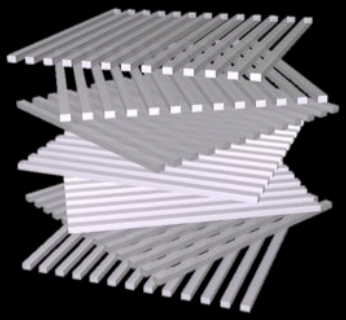


Opals

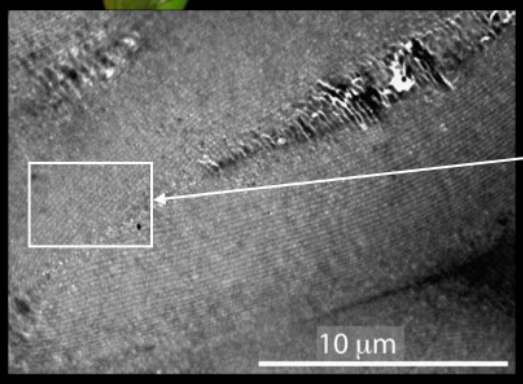
Photonic crystal in nature

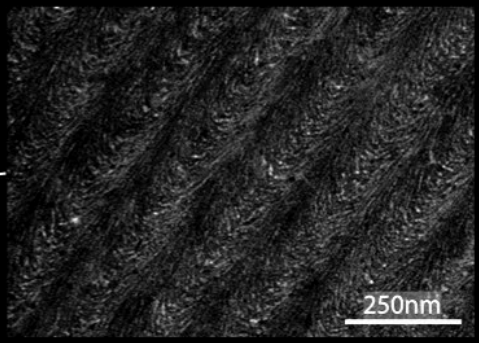
Plants





Pollia condensata

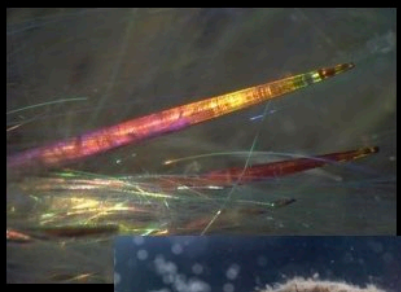




Courtesy Silvia Vignolini

Photonic crystal in nature

Animals, invertebrate

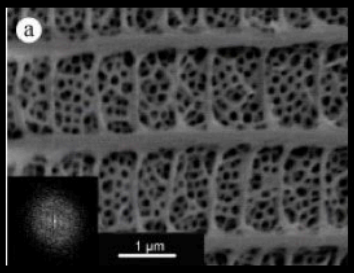


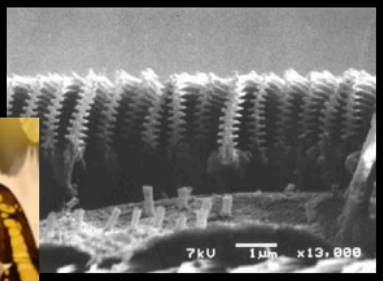
Chrysolina fastuosa

Sea mouse, Polychaeta: Aphroditidae: Aphrodita sp.

Photonic crystal in nature

Animals, invertebrate





Morpho menelaus didius butterfly

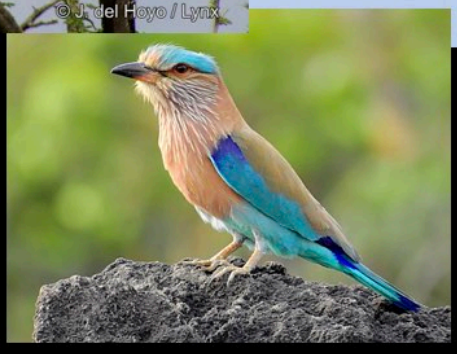
Photonic crystal in nature

Animals, vertebrate

Anna's hummingbird (Calypte anna)

Photonic crystal in nature

Animals, vertebrate



Indian roller (Coracias benghalensis (syn. Coracias indica))

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By Sir C. V. Raman, Kt., F.R.S., N.L.
Indian Institute of Science, Bangalore.
Received May 28, 1934.

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1888 -1970