

Photonic crystals, PHYS-605

Ecole doctorale photonique

Romuald Houdré

Summer semester 2017

Introduction

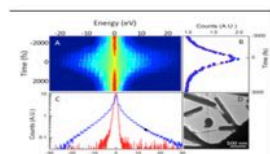
Romuald Houdré, FSB, IPHYS, GCMP, LASPE, romuald.houdre@epfl.ch, 35487



EPFL | PAR PUBLIC | PAR FACULTÉ | EPFL EN BREF | Personnes

INSTITUT DE PHYSIQUE IPHYS

Plateformes | Organigramme | Actualités | Postes à pourvoir | Contacts | A propos d'IPHYS



- L'activité de recherche de l'Institut de Physique couvre :
- Physique de la matière condensée
 - Physique des hautes énergies et des particules
 - Physique des systèmes biologiques
 - Physique théorique

Actualités

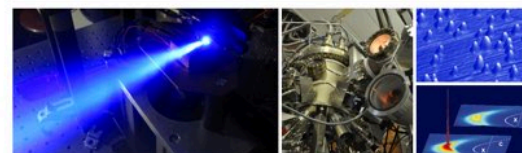
RECHERCHE
New material offers stable
20.09.16 Skyrmions are elec
EPFL scientists have now disc
a wide range of temperatures.



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ADVANCED SEMICONDUCTORS FOR PHOTONICS AND ELECTRONICS LAB LASPE

News | Research | People | Facilities | Publications | Events | Funding | Collaborations | Education



Skills of LASPE

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Local PH D3 325 | nadja.favre@epfl.ch

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Switzerland

News

- Best Student Paper Award at SPIE Photonics Europe for Ian Rousseau
- Hybrid growth promises better green lasers [Read the research review on Compound Semiconductors](#)
- Continuous Wave Blue Lasing in III-Nitride Nanobeam Cavity on Silicon [Nano Letters 15 1259 \(2015\)](#)
- InGaN laser diodes emitting at 500 nm with p-layers grown by molecular beam epitaxy [Appl. Phys. Express 8 022105 \(2015\)](#)
- 94-GHz large-signal operation of AlInN/GaN high-electron-mobility transistors on silicon with regrown ohmic contacts [IEEE Electron Device Lett. 36 17 \(2015\)](#)
- Low temperature p-type doping of (Al)GaN layers using ammonia molecular beam epitaxy for InGaN laser diodes. [Appl. Phys. Lett. 105 241103 \(2014\)](#)
- Millimeter-wave performance of gallium nitride transistors on silicon. [Read the News Feature article on Semiconductor Today](#)

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 (\approx 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. Sibilía, 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

* **I Introduction, overview.**

Introduction
History of photonic crystals
The key concepts

* **2 Theory**

Main equations
Band structures and projected band structure
Plane wave expansion method
FDTD
Transfer matrices, FEM and other methods

* **3 Basic properties**

Mirror
Waveguide
Bends, splitters, couplers
Optical resonator
High quality factor cavities
Dispersion diagram and equifrequency surfaces
Superprism, negative refraction
Selfcollimation
Fourier analysis of Bloch waves

* **4 Fabrication techniques**

Epitaxy, patterning, etching
2D, III-V, Si, SOI
3D, Opals

* **5 Measurement techniques**

External light source
Internal light source
Advanced techniques

* **6 Applications**

Couplers
Polarizer and rotator
Modulator, routing
Add/Drop
Spectrometers and interferometers
Point defect photonic crystal lasers
Band-edge photonic crystal lasers

* **7 Emerging topics**

Integration with microfluidics systems
Biology
Slow light
Nano-beam
Subwavelength structures
Slotted waveguides
Sensors
Optical trapping
Optomechanic systems
Dynamic control
Non-reciprocal structures
Topological photonic structures
Novel materials (chalcogenide, diamond, GaN,...)
Thermal photovoltaic
...

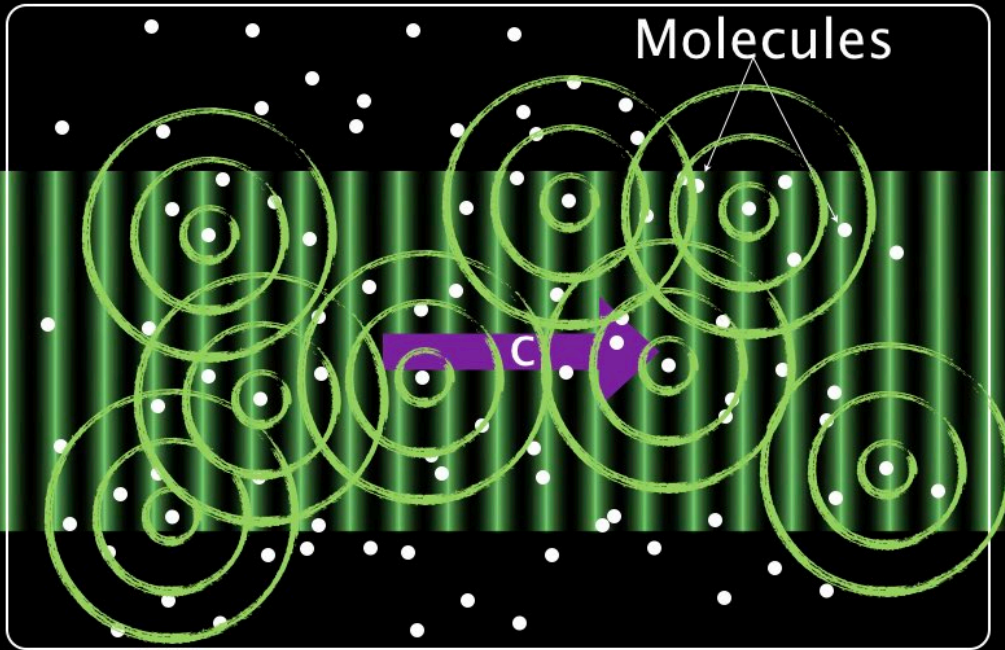
What the lecture is about :

a short introduction on photonic crystals

Three languages for one object

Light propagation in matter

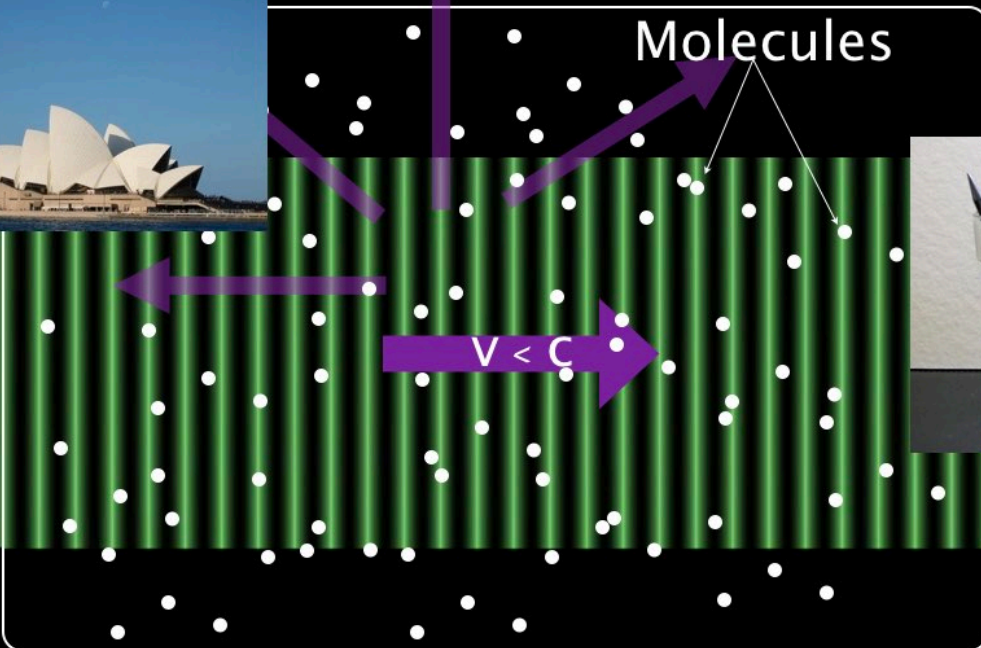
Three languages for one object



Molecules

Light propagation in a vacuum

Three languages for one object

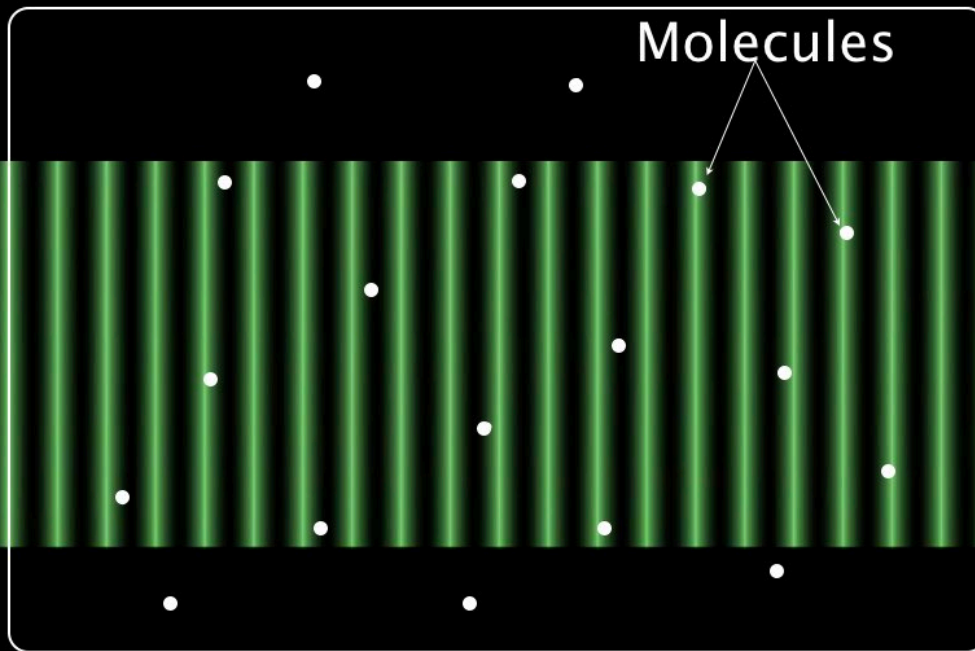


Molecules

Light propagation in matter

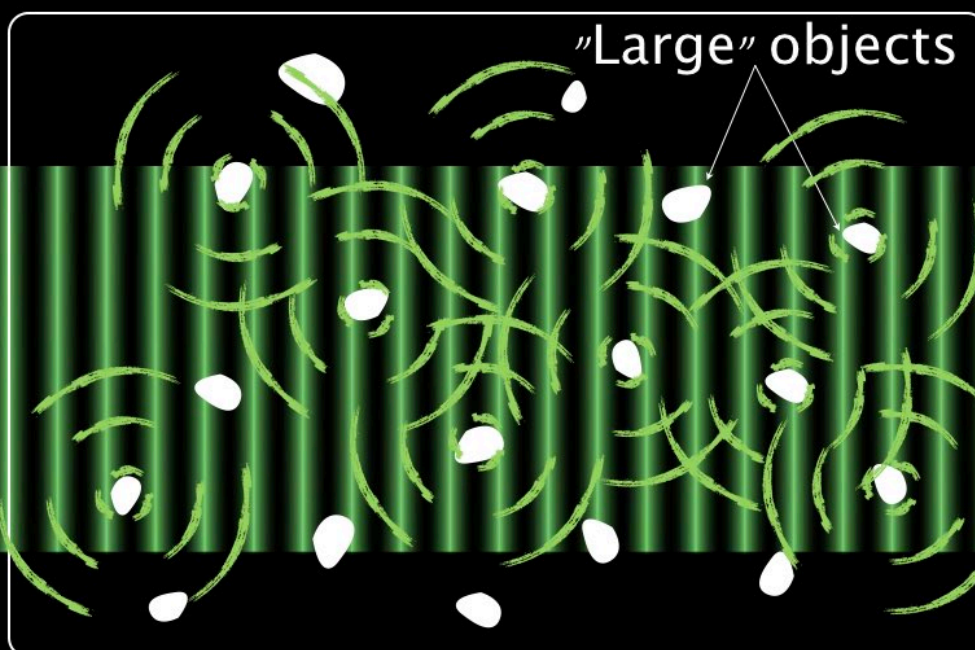


Three languages for one object



Light propagation in matter

Three languages for one object



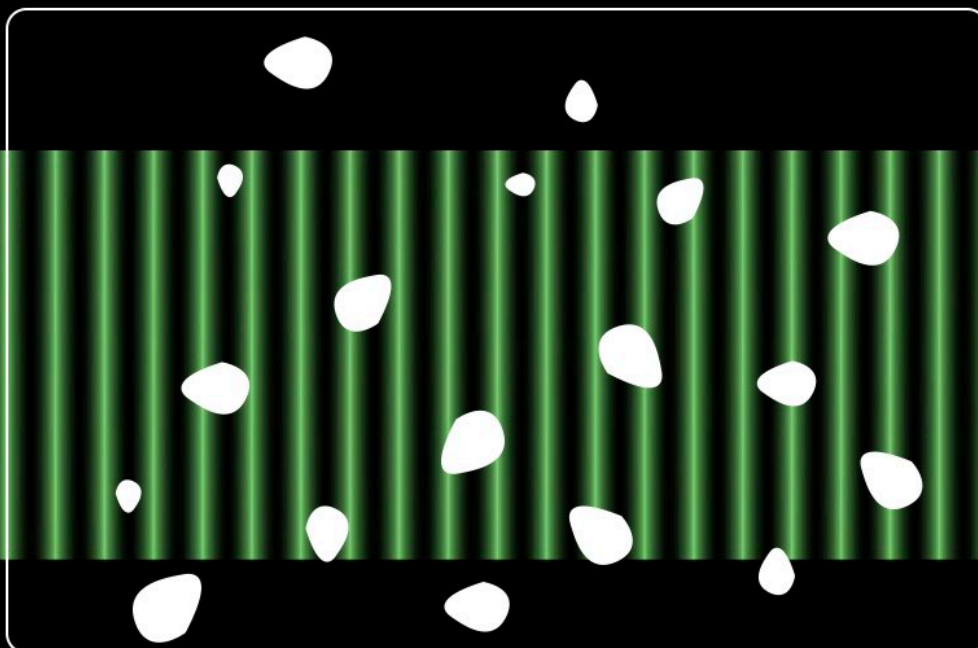
Light propagation in matter

Three languages

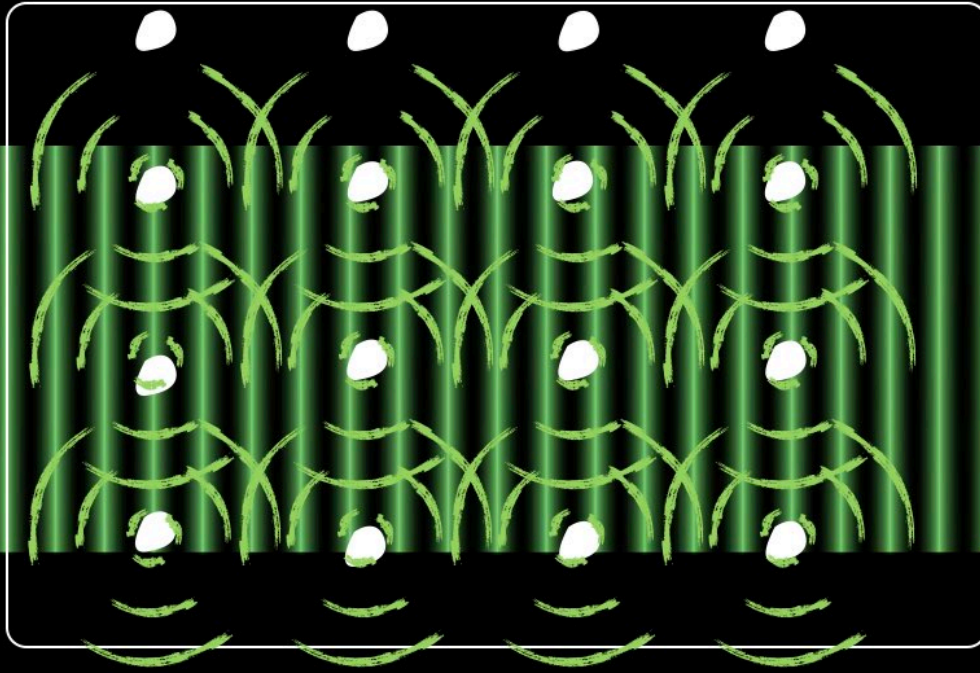


Light propagation in matter

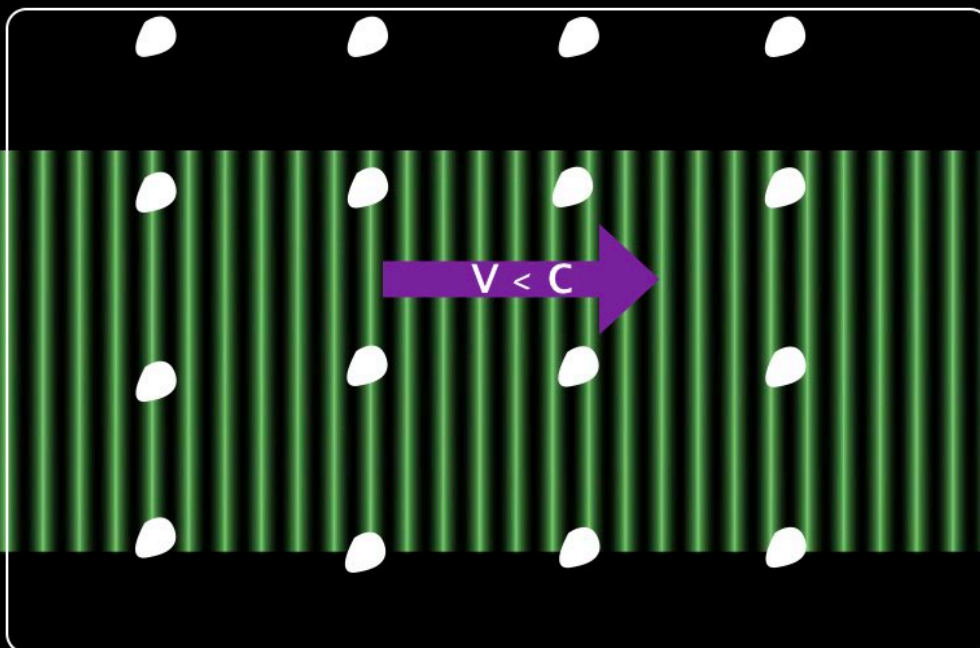
Three languages for one object



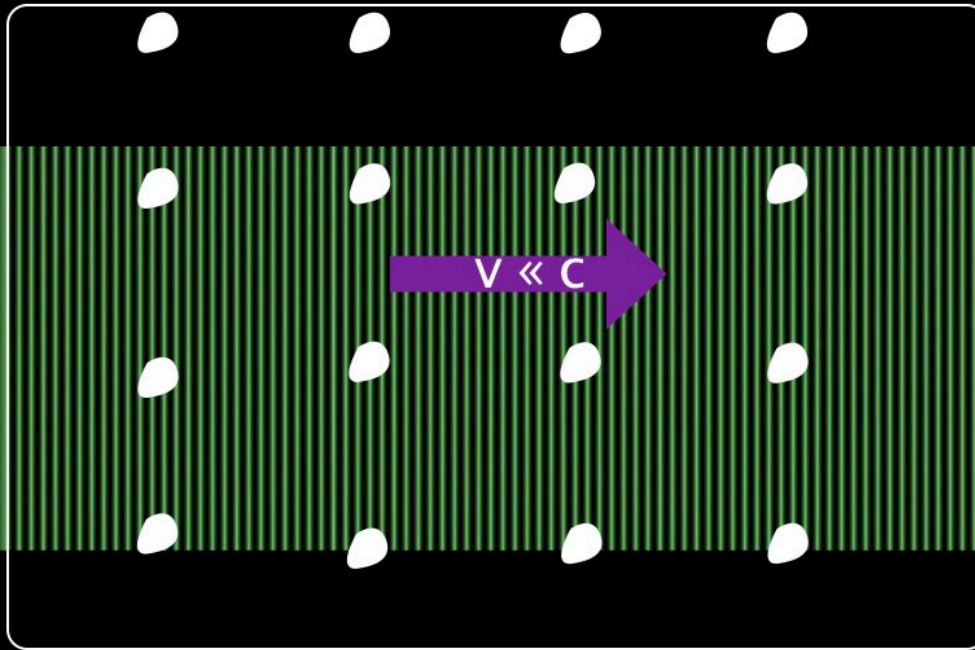
Three languages for one object



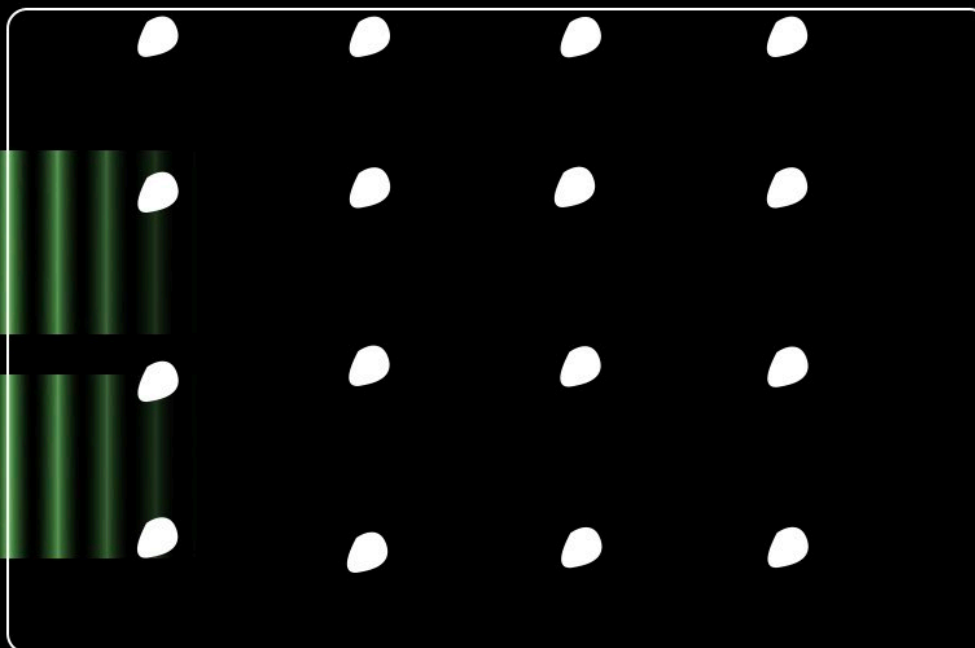
Three languages for one object



Three languages for one object



Three languages for one object



Photonic crystal

Three languages for one object

Physicist

Electrons in a crystal

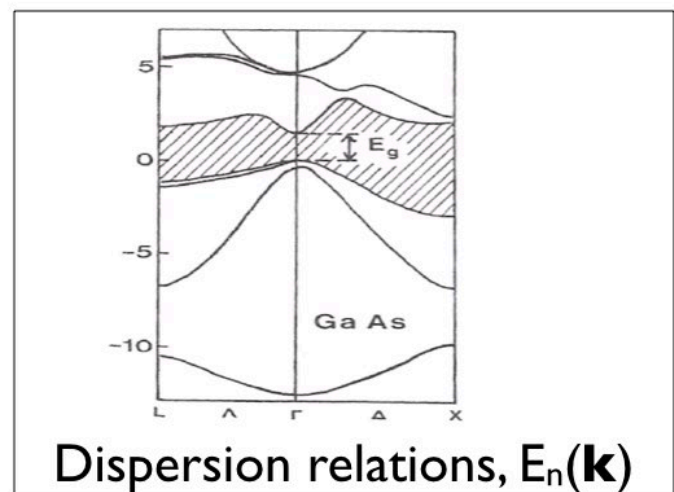
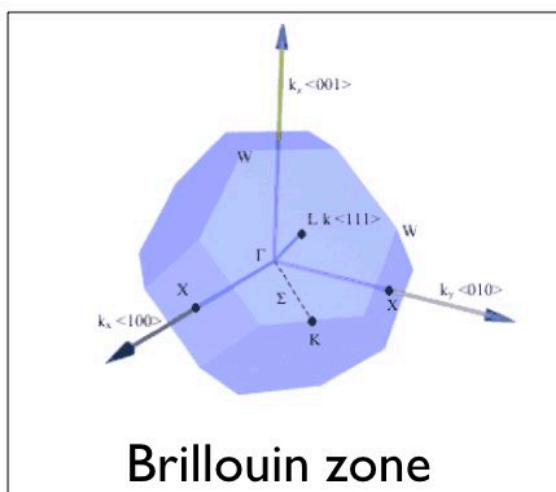
Crystal field, periodic potential $V(\mathbf{r})$

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

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

Three languages for one object

Physicist



* 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 lossless medium

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

Periodic refractive index $n(\mathbf{r})$

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

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

Three languages for one object

Physicist

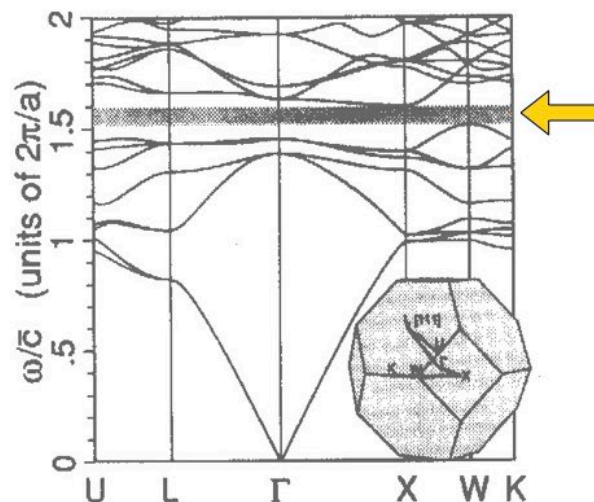
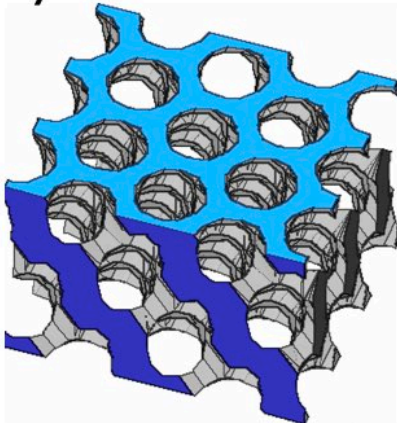


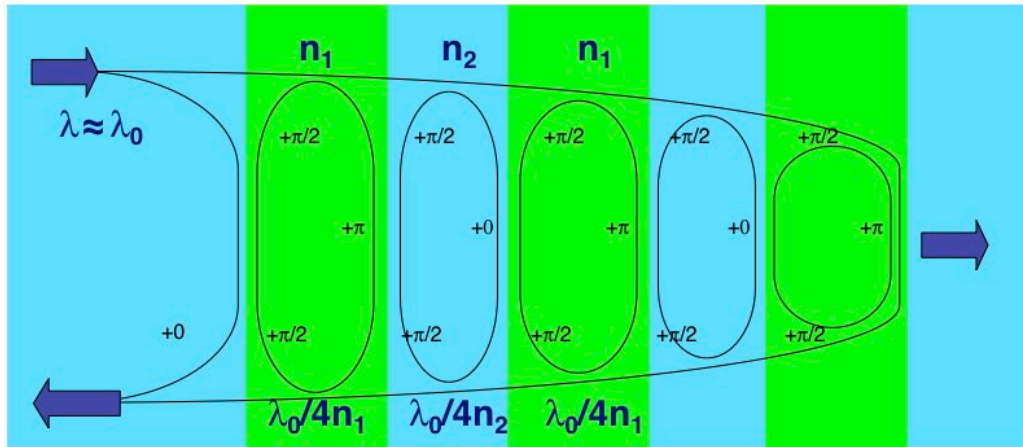
Figure 14: Band structure for EM waves for close-packed air spheres on a FCC lattice. $\bar{c} \equiv c/\sqrt{\epsilon}$. $\epsilon_b = 13$, $\epsilon_a = 1$, $\beta = 0.74$, $\|\epsilon_r\| = 1.34$, $N = 749$. Inset shows the path in the BZ. (From Ref. [20])

* Band of allowed states, propagation is possible

* Band with no allowed states, propagation is impossible

Three languages for one object

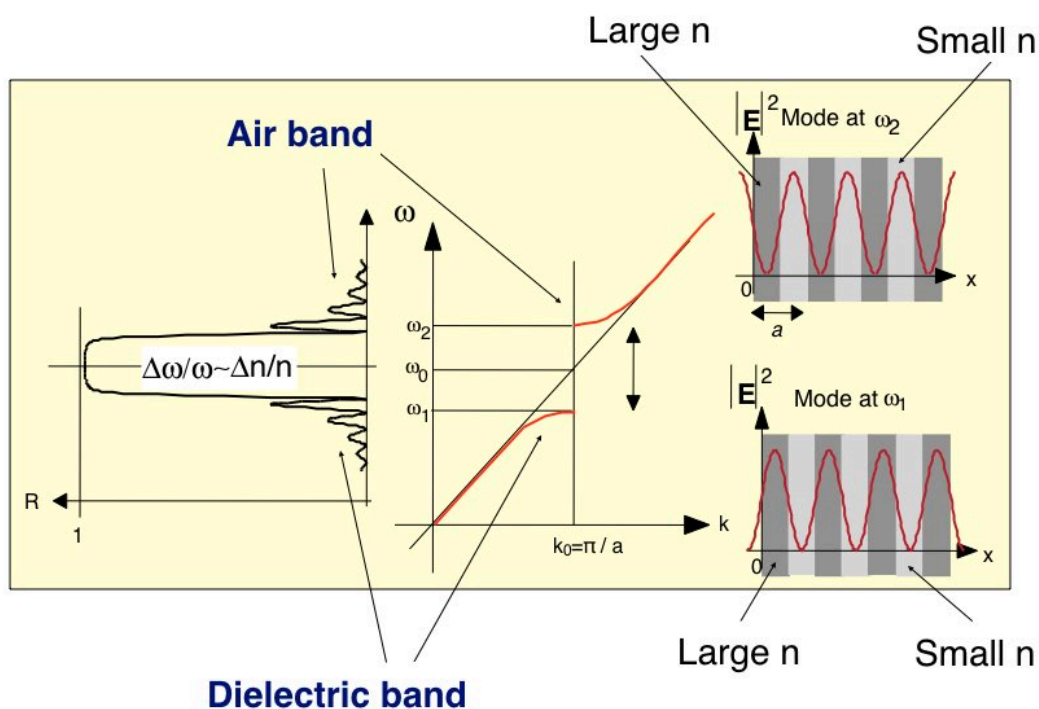
Wave optics Bragg mirror: multilayers
refractive index n_1 and n_2



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

Three languages for one object

Wave optics

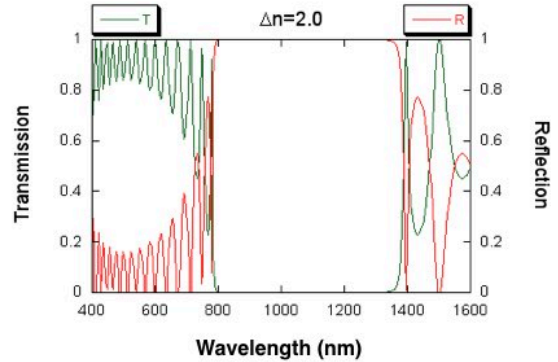
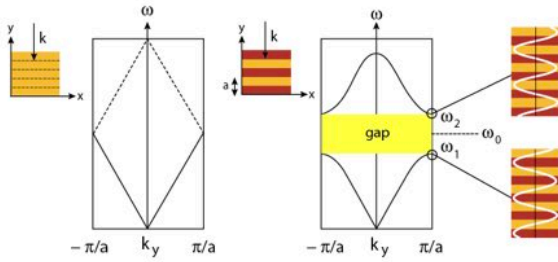


Three languages for one object

Wave optics bis, coupled modes

Periodic dielectric structure 1D

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



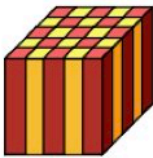
Coupled modes

Forbidden band around normal incidence

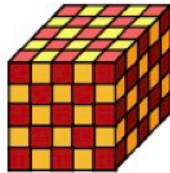
1D



2D



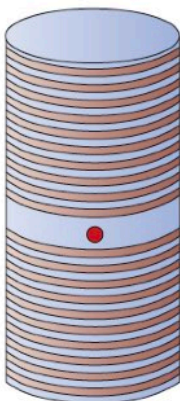
3D



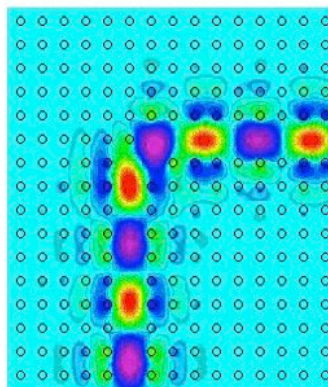
Periodic dielectric structure 3D

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

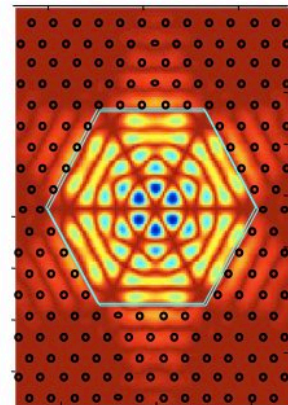
Like in semiconductors, richness of the field will come from the possibility to insert defects and impurities



Bi-dimensional defect
Planar cavity



One-dimensional defect
Wave guide



Point defect
Optical cavity

Photonic crystal zoology

Refractive index modulation

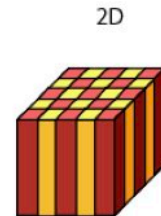
✳ in 1 direction of space

- multilayer stack of dielectrics



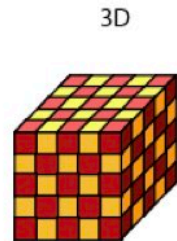
✳ in 2 directions of space

- lattices in planar waveguides
- microporous systems



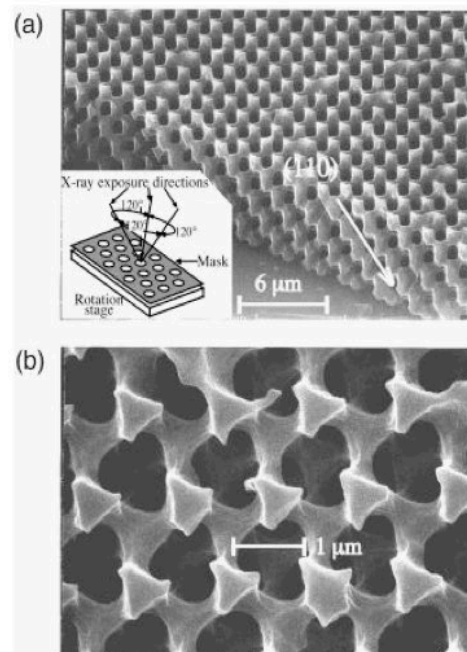
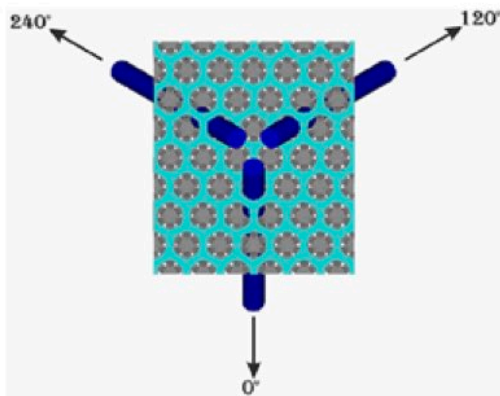
✳ in 3 directions of space

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



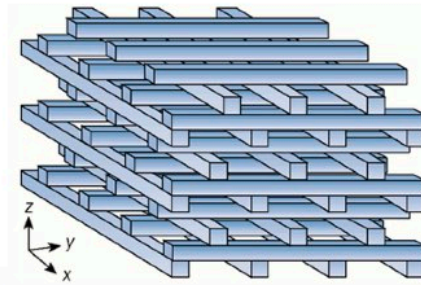
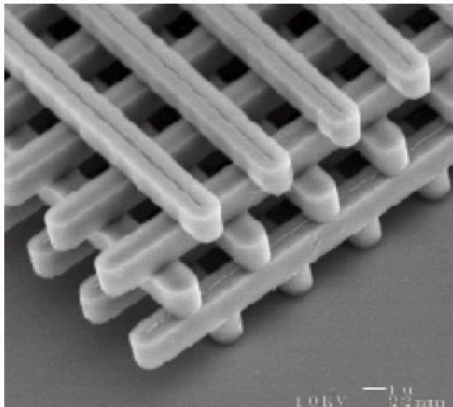
Photonic crystal zoology, 3D

Etching (Yablonovite)

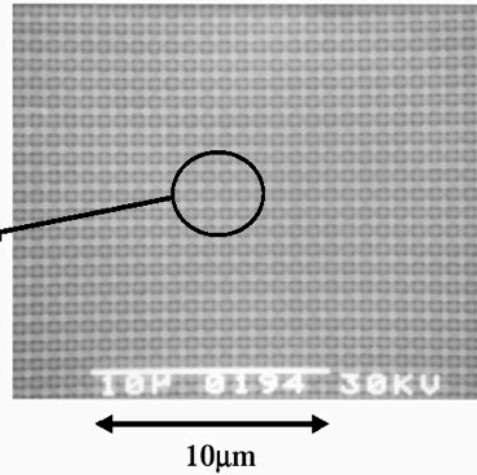
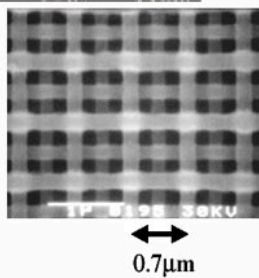


Photonic crystal zoology, 3D

Micro-fabrication

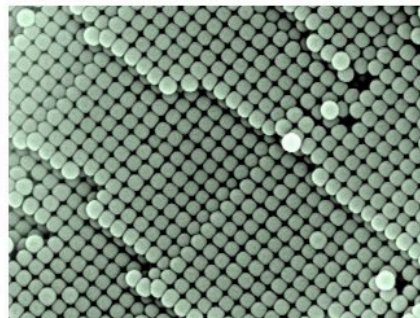
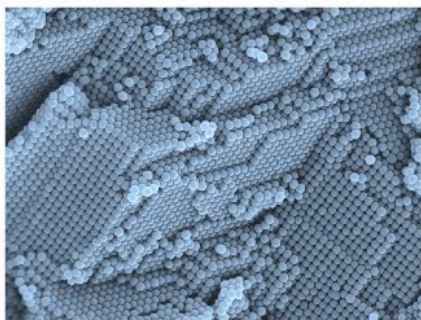


"Wood pile"



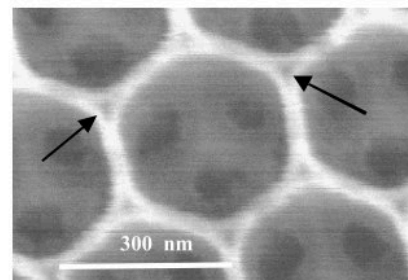
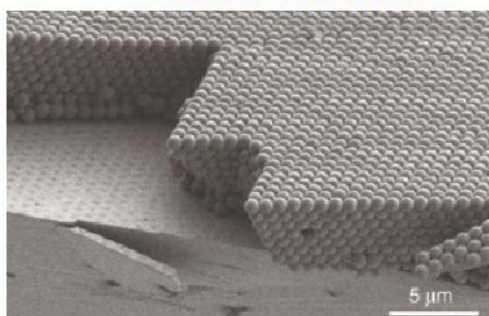
Photonic crystal zoology, 3D

Self-organized



Opals

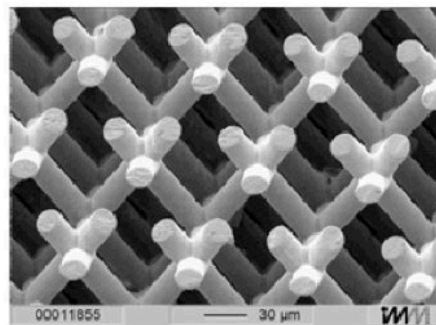
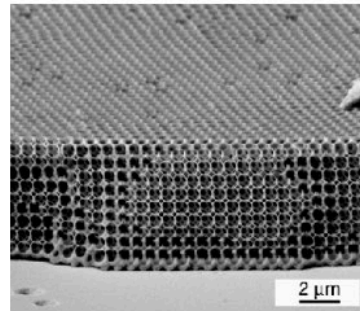
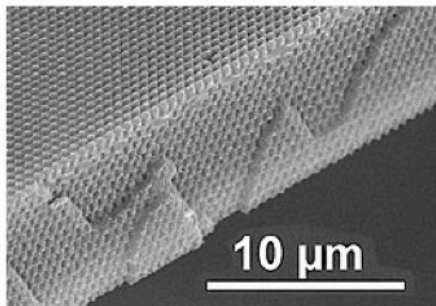
Silica or latex stacks



inverted structures by infiltration and selective etching

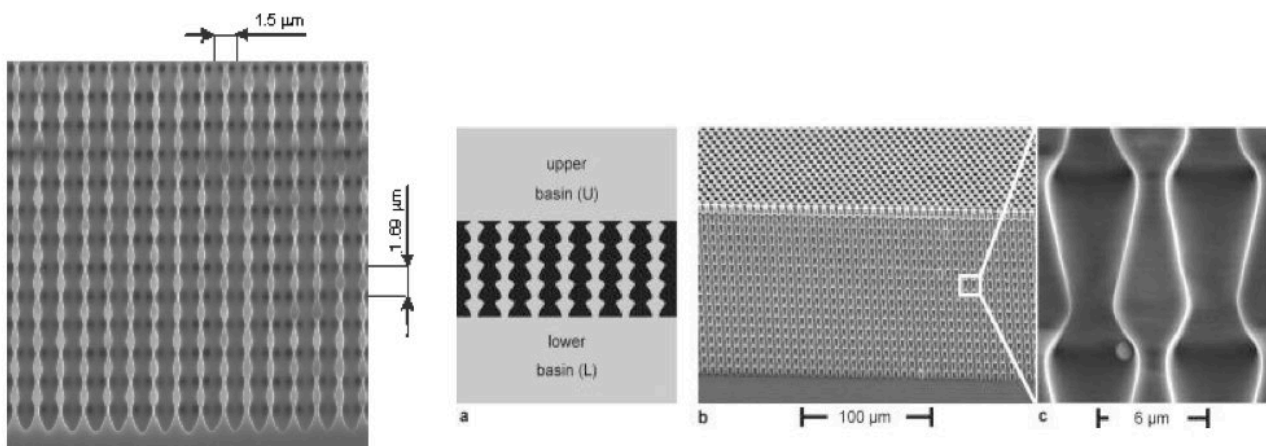
Photonic crystal zoology, 3D

Holography



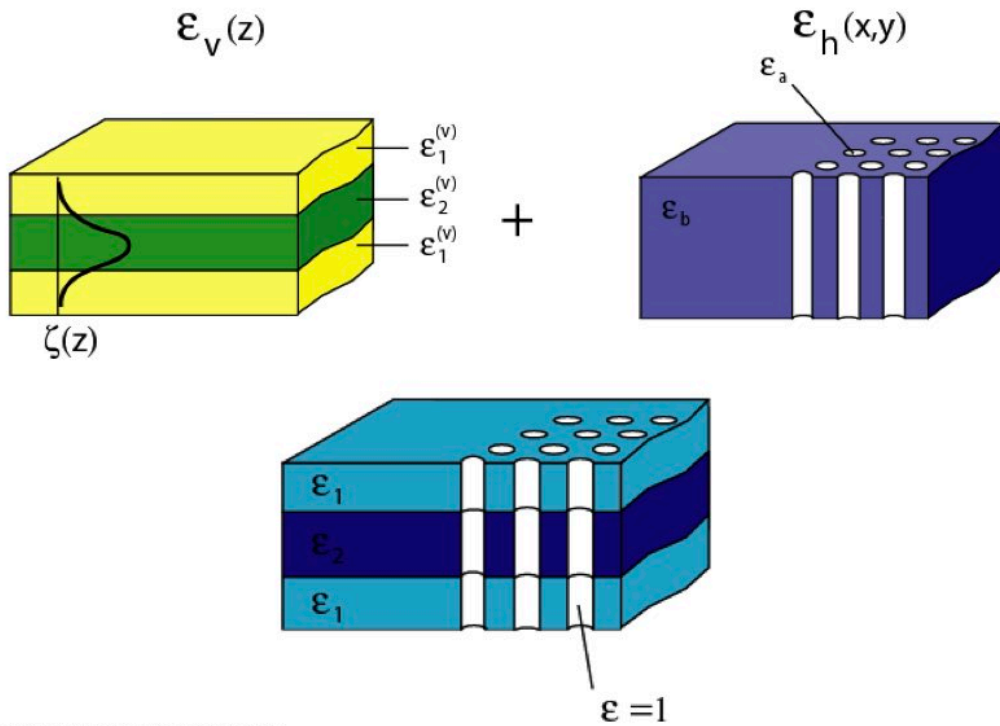
Photonic crystal zoology, 3D

Microporous silicium (anodization)



Photonic crystal zoology, 2D

2D patterning + planar waveguide



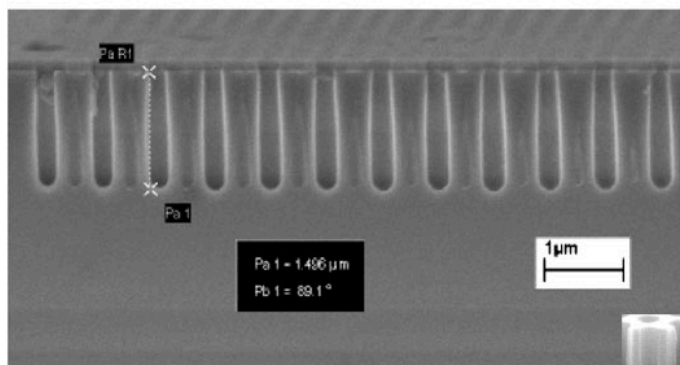
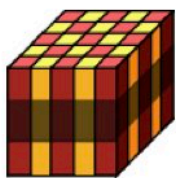
Photonic crystal zoology, 2D

2D patterning + planar waveguide

Planar waveguide, low index contrast

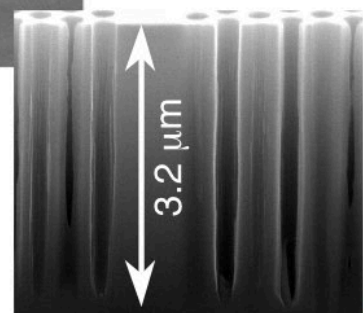
$$|n_1 - n_2| \ll n$$

"2+1" D



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

GaAs / Al_xGa_{1-x}As

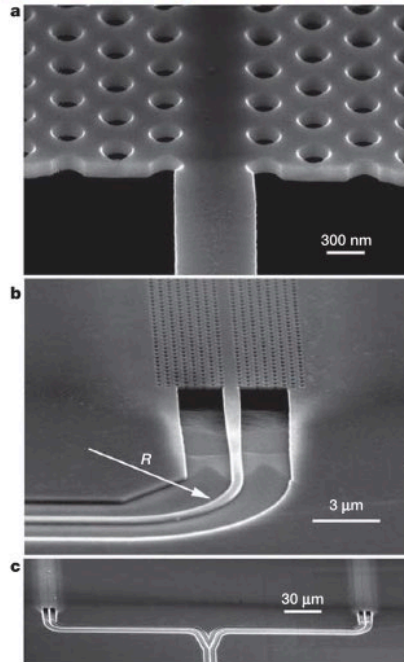
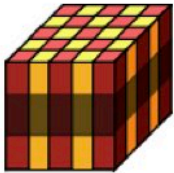


Photonic crystal zoology, 2D

2D patterning + planar waveguide

Planar waveguide, large index contrast

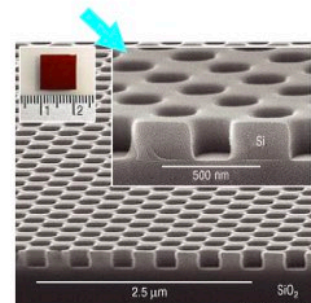
"2+1" D



$$n_1 - n_2 \gg n$$

membrane
air/Si
GaAs /air
InP/air

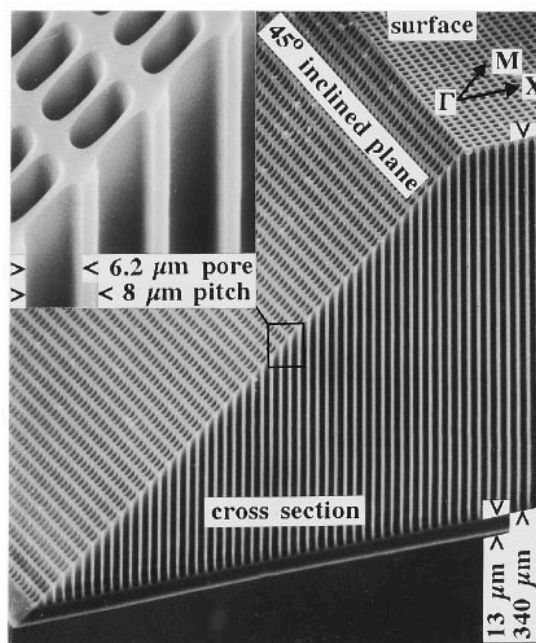
air/Si/SiO₂
air/InP/BCB



Photonic crystal zoology, 2D

Pure 2D objects

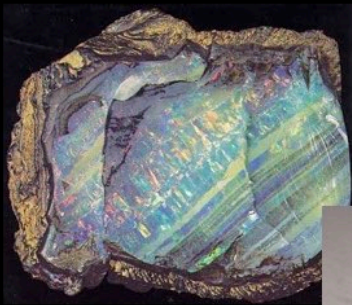
Infinitely extended in the third dimension



Si microporous

Photonic crystal in nature

Mineral



Opals

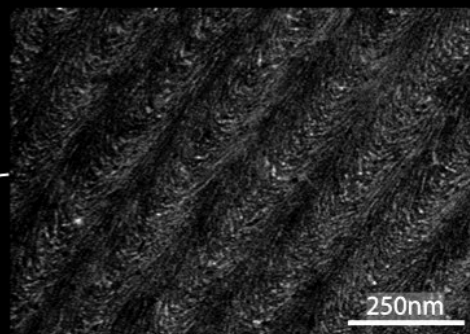
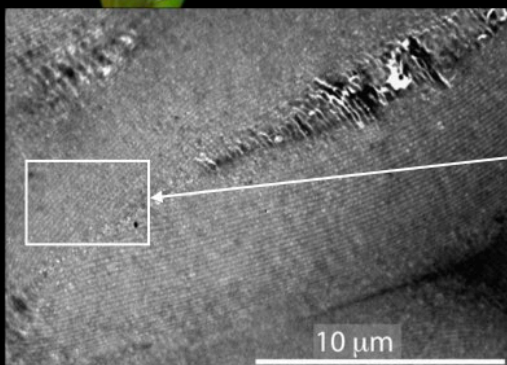
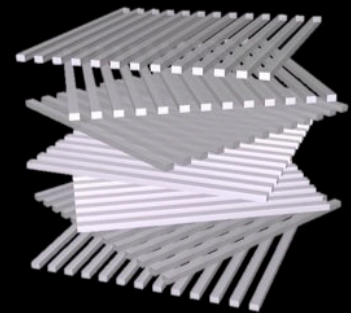


Photonic crystal in nature

Plants



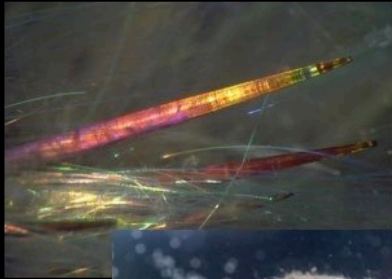
Pollia condensata



Courtesy Silvia Vignolini

Photonic crystal in nature

Animals, invertebrate



Chrysolina fastuosa



Sea mouse, Polychaeta: Aphroditidae: *Aphrodita* sp.

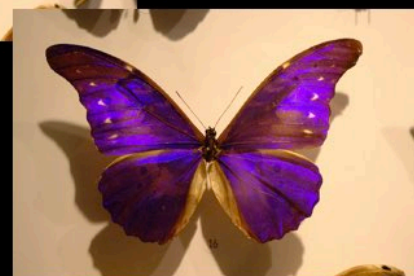
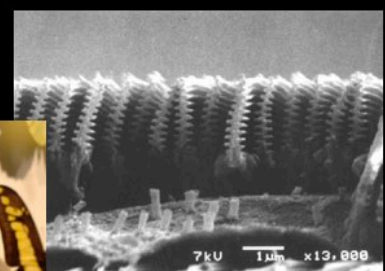
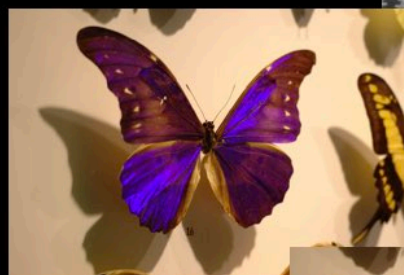
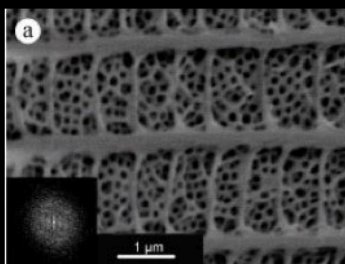
Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

0.39 / 0.42



Photonic crystal in nature

Animals, invertebrate



Morpho menelaus didius butterfly

Ecole doctorale photonique, Photonic crystals, PHYS-605, Romuald Houdré, Summer semester 2017

0.40 / 0.42



Photonic crystal in nature

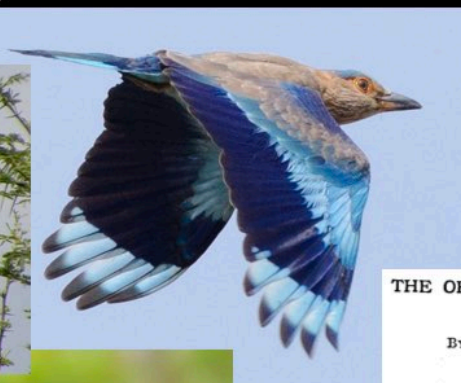
Animals, vertebrate



Anna's hummingbird (*Calypte anna*)

Photonic crystal in nature

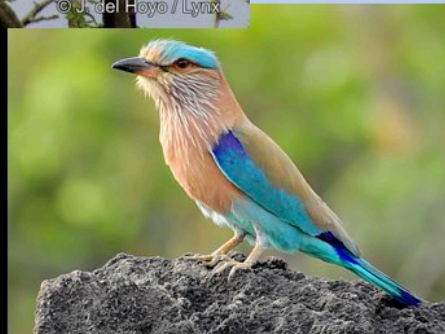
Animals, vertebrate



THE ORIGIN OF THE COLOURS IN THE PLUMAGE OF BIRDS.

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1888 -1970

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