Photonic crystals, PHYS-605

Ecole doctorale photonique

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Summer semester 2017

Introduction
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
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. Sibilla, 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 band gaps and localization** / ed. C. M. Soukoulis, New York : Plenum

- **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
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

Molecules

Light propagation in matter

Three languages for one object

"Large" objects

Light propagation in matter
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

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 lossless 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 $\omega_n(k)$, $n$ integer, $k$: wavevector

Three languages for one object

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

Air band

Dielectric band

Large $n$ Small $n$ Large $n$ Small $n$
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

**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"

Self-organized

Opals

Silica or latex stacks

inverted structures by infiltration and selective etching
Photonic crystal zoology, 3D

Holography

Microporous silicium (anodization)
Photonic crystal zoology, 2D

2D patterning + planar waveguide

\[ \epsilon_v(z) + \epsilon_h(x,y) \]

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Photonic crystal zoology, 2D

2D patterning + planar waveguide

Planar waveguide, large index contrast $n_1 - n_2 >> n$

- membrane
- air/Si
- GaAs/aic
- InP/air
- air/Si/SiO$_2$
- air/InP/BCB

Pure 2D objects
Infinitely extended in the third dimension

Si microporous
Photonic crystal in nature

Mineral

Opals

Photonic crystal in nature

Plants

Polia condensata

250nm

10 μm

Courtesy Silvia Vignolini
Photonic crystal in nature

Animals, invertebrate

Sea mouse, Polychaeta: Aphroditidae: Aphroditia sp.

Chrysolina fastuosa

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))

Chandrashekhar Venkata Raman
1888 - 1970

www.abw.com/ibc