Photonic crystals, PHYS-605

Ecole doctorale photonique

Romuald Houdré

Summer semester 2017

VII Emerging topics

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   Optomechanic systems
   Dynamic control
   Non-reciprocal structures
   Topological photonic structures
   Novel materials (chalcogenide, diamond, GaN, ...)
   Thermal photovoltaic
   ...
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
- ...

Optical trapping

Rita Therisod's presentation

Topological structures

Liu Qiu's presentation
Microfluidics

+ Rita Therisod's presentation

Hybridisation with other complex technologies


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Microfluidics

Review article C. Monat et al., Nat. Phot., 1, 106 (2007)

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Biology

Many ideas
- Grafting, trapping of single molecules (DNA, protein, ...)
- Selective optical detection of a molecule or a luminescent specific marker
- Make use of the large emission increase due to resonances

Presently, mainly detection schemes based on refractive index change, for example N. Skivesen et al., Opt. Exp., 15, 3169 (2007)
- Little selectivity
- Associated Δn are often very small
- A few examples of functionalization

Selectivity is achieved by grafting of molecules at a functionalized surface in the holes


Slow light

+ Morteza Navadeh's presentation

Motivation
- Enhancement of linear effects for a constant length - n_x
  - Delay line, buffer memory (≈ max a few 100 bits)
  - Commutation (for devices based on a Δk variation)
  - Sensors
- Polynomial enhancement of non-linear effects - n_x^n
  - Diminution of the interaction length
  - Enhancement also due to intensity increase, J = ρ.v_x if v_x \rightarrow then ρ \rightarrow
- Quantum optics

Issues
- Bandwidth
- Propagation losses
- Coupling
- Dispersion
- Disorder

Review articles:
Slow light

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Slow light

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Slow light

Example of application in a Mach-Zehnder

- Commutation


Slow light

Some approaches

- Band edge
  - dispersion
  - losses
  - back reflection

Slow light

Some approaches

- Dispersion engineering
  - outside band edge, zone boundaries etc...
  - Spatial compression of the pulse

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Slow light

Some approaches

- Dispersion engineering

Shifted rows

\[ n_g \approx 30 \]

Low group velocity dispersion

Robustness

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Slow light

Some approaches
- Dispersion engineering

Shifted rows

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Slow light

Some approaches
- Coupled cavities waveguides (CCW)

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\[ n_g \approx 50 \]

\[ v_g(K) = -\frac{d\omega_K}{dK} = -\Omega R \kappa_1 \sin(KR) \]
\[ \omega_K = \Omega \left[ 1 - \frac{\Delta \alpha}{2} + \kappa_1 \cos(KR) \right] \]

Coupling strength determines the dispersion curve (tight binding)
Slow light

Some approaches
- Coupled cavities waveguides (CCW)
  - Transmission spectrum

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Slow light

Well sold, but ... a flat transmission spectrum is mandatory

\[\Delta \tau = (n_e - n_{ref}) \frac{L}{c}\]

Echoes, cavity ring-down

Slow light

Some approaches
- Dynamic structures, see next sections

Commutation between fast and slow regime is achieved in changing the coupling constant

Slow light

**Application**  
<table>
<thead>
<tr>
<th>Figure of merit $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single frequency</td>
</tr>
<tr>
<td>Delay line</td>
</tr>
<tr>
<td>Buffering</td>
</tr>
<tr>
<td>Non-linear effect</td>
</tr>
<tr>
<td>Spatial frequencies</td>
</tr>
<tr>
<td>Normalised delay</td>
</tr>
<tr>
<td>Inclusion of losses</td>
</tr>
</tbody>
</table>

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Slow light

**Intrinsic limits due to periodicity**

\[
\Delta k \leq \frac{\pi}{a} \quad \text{or} \quad \Delta \tilde{k} \leq \frac{1}{2} \quad \text{or} \quad n_g \Delta u/u \leq \frac{1}{2u} = \frac{\lambda}{2a} \quad \text{or} \quad \frac{\lambda}{2\Lambda} \quad \text{for a CCW, } \Lambda=Na
\]

Usually, $u \approx 0.25-0.3$ and $n_g \Delta u/u \text{ max } 1.7 - 2$ (or 1.7 - 2 / N for CCW)
Slow light

Intrinsic limits due to periodicity

Current values:

**Modified WI**
(e.g. N. Le Thomas et al., Phys. Rev. B 76, 035103 2007)

\[ n_g \frac{\Delta u}{u} \leq \frac{1}{2u} = \frac{\lambda}{2a} = 1.7 - 2 \]

\[ n_g \Delta u/u = 0.25 \]

×10 margin for improvement

**CCW**
(e.g. J. Jägerská et al., Opt. Lett. 34, 359 2009)

\[ n_g \Delta u/u = 0.18 \]

×2 margin for improvement

close to the limit

\[ n_g \Delta u/u = 0.1 \]

**CCW**
(e.g. M. Notomi et al., Nat. Phot. 2, 741 2008)

Slow light

Intrinsic limits due to dispersion

To be avoided:

- **GVD**
  Pulse propagation

- **Zone center**
  Radiative intrinsic losses (always the case for a CCW)

- **Zone boundary and band edge in general**
  Backscattering, proximity of the backward propagating mode. \( \Delta k_{\text{scattering}} \approx 1/l_{\text{disorder}} \)

- **Evanescent modes**
  Coupling, disorder

Desired:

- Flat dispersion in the middle of the Brillouin zone below the light cone
Slow light

Extrinsic limits

- Residual disorder

- Light-matter increased interaction due to slowing the light (i.e. increasing the density of states) applies also to interaction with defects such as disorder

- Disorder induced propagation losses \( \propto n_g \) (linear response)

- Disorder induced back-scattering losses \( \propto n_g^2 \) (density of states factor is involved twice)

- For larger disorder/\( v_g \), wavevector loses its relevance
  - Dispersion relations and group velocity cannot be defined anymore
  - Light still propagates through the medium, but only and energy propagation velocity \( v_E \) can be defined

- For even larger disorder/\( v_g \), Anderson light localisation (i.e. absence of light propagation in the presence of disorder). Beware: not described by perturbative approaches to any order.
Slow light

Extrinsic limits

- For larger disorder/\nu_g, wavevector loses its relevance

![Graph showing dispersion curve, surface emission, and waveguide transmission with regions labeled dispersive regime, diffusive regime, localized states, and reduced energy u.]


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Slow light

Extrinsic limits

- Fast light / slow light transition

Mode mismatch is responsible for strong backscattering and out-of-plane insertion losses

- High \nu_g, low \nu_g transition taper

- AR PhC intermediate layer

- Topology optimisation
  5dB improvement but still ~20dB

Slow light

Extrinsic limits
- Fast light / slow light transition
- Interplay with interface and evanescent modes

- Optimized hole termination, interplay with interface modes

J. Jägerská, PhD dissertation, EPFL n°4956 (2010)
Slow light

State of the art

- $n_g \approx 30$
  

- $n_g \approx 50$
  

- $n_g \approx 100$
  

- $n_g \approx 30$
  

- $n_g \approx 100$
  


Non linear effect, example: third harmonic generation

B. Corcoran et al., Nat. Phot., 3, 206 (2009)
Nanobeam

- High Q
- Large Q/V → quantum optics, microlaser ...
- Ease of fabrication
- Cavity access → tuning, sensors
- Optomechanic applications

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Nanobeam


\[ Q_{\text{exp}} = 750,000 \]

\( \rightarrow \) optomechanic systems
\( \rightarrow \) slotted guides
\( \rightarrow \) sensors


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Slotted guides

Guides with low index core / empty
How to obtain guided mode in air

- Quantum optic
- Sensor; analyte is introduce in the core
- Insertion of active low index material (non-linear polymer ...)

Implementation in photonic crystals of an approach used in optical nanowires


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Slotted guides


Slotted guides / sensors

Slotted guides / sensors

Slotted WI waveguide
a = 510 nm, f = 0.36, s = 120 nm

Cavity:
Slot 100-120-100 nm
3a cavity, 5a barrier
Slotted guides / sensors

Quality factor
$Q = 26\,000$

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Slotted guides / sensors

Wavelength shift of the cavity resonance upon exposure to gasses

$40$ attoliters $= 0.04$ µm$^3$
$= 1.8$ attomol
$= 7.2$ attogram (He)
$\approx 10^6$ molecules

Sensitivity $= 610$ nm/RIU

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Sensors

Arbitrary selection of a few examples
- Most of the time, simply a refractive index sensor
- Little selectivity in itself
- See also, microfluidic and slotted guides sections

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Sensors

A little bit more elaborated
\[ V = 0.15 \, \mu m^3 / 1 \, fg \]

Final goal: functionalize the sphere surface

Without sphere

With sphere

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Sensors

Integrated in a μfluidics environment

Functionnalized holes
Label free
Refractive index detection limit $7 \times 10^{-5}$
10 attograms

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Sensors

Integrated in a μfluidics environment

Functionnalized holes
Label free
Sensitivity : 64.5 nm/RIU
2.3 $\times 10^{-5}$ nm/M
1.5 fg of human IgG

S. Pal et al., Biosensors Bioelec., 26, 4024 (2011)
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Sensors

A more original approach to obtain optical field in air
- Heterostructure cavity
- Surface mode + open holes
- Measurement $\lambda_{\text{Laser}}(n)$
- 625 nm/RIU or $\Delta n = 3.6 \times 10^{-6}$ (modelling)

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Dynamic control

+ Antoine Delgoffe’s presentation

Control in time of the optical properties of the structure
Example : quality factor of a cavity

$\tau_{\text{input}}$  
Low Q, in-coupling fast and efficient

$\tau_{\text{storage}}$  
High Q, long lifetime of the pulse in the cavity

$\tau_{\text{readout}}$  
Low Q, out-coupling fast and efficient
Dynamic control

Control in time of the optical properties of the structure

Other more advanced applications:

- Translational invariance $\Rightarrow$ $k$ conservation

- Structure non-translational invariant $\Rightarrow$ No $k$ conservation $\Rightarrow$ Chirped structures

- Time invariant structure $\Rightarrow$ Energy conservation

- Time dependant structure $\Rightarrow$ No energy conservation $\Rightarrow$ Dynamic control

Dynamic control

Dynamic control of the quality factor of a cavity


Y. Tanaka, Nat. Mat., 6, 862 (2007)
Dynamic control

Trap and release of a pulse and frequency shift


Non-reciprocal systems

+ Liu Qiu’s presentation

Very active topic also in the metamaterials field

Needed functionality in many optical systems

Require systems with time invariance symmetry breaking \((t \rightarrow -t)\) or time-dependent structures

- Magneto-optical materials

- Non-linear effects

- Non centro-symmetric structures
  - chiral structures (metamaterials)

Beware that there are several deeply wrong papers in this field, which misunderstand what an optical insulator actually is.

Little compatibility with integrated optics technologies

Improper

Improper
Non-reciprocal systems

Oblique transitions with breaking of
- translational invariance $\Delta k$
- temporal invariance $\Delta \omega$

Refractive index modulation $\cos(\Omega t + qz)$
- non symmetric to couple odd and even modes
- $\Omega \rightarrow \Delta \omega$
- $q \rightarrow \Delta k$
- bandwidth depends only from the ability to design waveguides with parallel dispersion curves

$\omega_1 \rightarrow \omega_2$
$\omega_1 \leftarrow \omega_1$

- Isolation
- Non-reciprocal frequency conversion

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Non-reciprocal systems

$L = 2L_c$

$\omega_1 \rightarrow \omega_2 \rightarrow \omega_1$
$\omega_1 \leftarrow \omega_1 \leftarrow \omega_1$

Purpose is to introduce a non-reciprocal $\pi$ phase shift

port 1 $\rightarrow$ port 3
port 2 $\leftarrow$ port 3

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Novel materials

- Chalcogenides
- SiC
- Diamond
- GaP
- GaN and III-N
- Deformable structures
  Nicola Bartolomei's presentation

Chalcogenides

Photorefractive, photo-induced metastables states

- Fabrication
- Trimming
- $\Delta n \approx 2.5$
- Fast non-linear effects (Kerr)

Chalcogenides

Tuning

Photowritten high-Q cavities


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GaN and III-N

Large bandgap material PhC, possible materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive index</th>
<th>Band gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN</td>
<td>2.6 @ 370 nm</td>
<td>3.4 eV</td>
</tr>
<tr>
<td></td>
<td>2.4 @ 500 nm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.39 @ 600 nm</td>
<td></td>
</tr>
<tr>
<td>AlN</td>
<td>2.17 @ 500 nm</td>
<td>6.2 eV</td>
</tr>
<tr>
<td>SiNₓ</td>
<td>≈ 2.0</td>
<td>3–4 eV</td>
</tr>
<tr>
<td>SiC</td>
<td>2.5–2.8</td>
<td>2.4–3.6 eV</td>
</tr>
<tr>
<td>SiO₂</td>
<td>≈ 1.45</td>
<td></td>
</tr>
<tr>
<td>ZnO</td>
<td>1.8–2.34</td>
<td>3.3 eV</td>
</tr>
<tr>
<td>GaP</td>
<td>3.25–3.44</td>
<td>2.2 eV</td>
</tr>
<tr>
<td>Diamond</td>
<td>2.37–2.67</td>
<td>5.5 eV</td>
</tr>
</tbody>
</table>
GaN and III-N

Suspended structures


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GaN and III-N

Record quality factor in GaN PhC

\[ Q_{\text{meas.}} = 44,000 \]
\[ Q_{\text{theo.}} = 80,000 \] (with injectors)

Optimized H0 cavity

Normalized resonant scattering intensity

\[ Q = 4.4 \pm 0.3 \times 10^4 \]

linewidth = 34 pm

Wavelength (nm)

APL Phot. 2, 0331301 (2017)
GaN and III-N

Continuous-wave 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonic generation

\begin{align*}
P_{\text{SHG}} &= 0.74 \text{ nW for 0.78 mW input coupled in the cavity} \\
P_{\text{SHG}} / P_{\text{coupled}}^2 &= 2.4 \times 10^{-3} \text{ W}^{-1}
\end{align*}

APL Phot. 2, 0331301 (2017)

That's all ...