ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Photonic crystals, PHYS-605

Ecole doctorale photonique

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Summer semester 2017

VII Emerging topics

Contents

- **1 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
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  - Waveguide
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  - High quality factor cavities
  - Dispersion diagram and equifrequency surfaces
  - Superprism, negative refraction
  - Selfcollimation
  - Fourier analysis of Bloch waves
- **4 Fabrication techniques**
  - Epitaxy, patterning, etching
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- **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
  - …

Emerging topics

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Optical trapping

Rita Therisod's presentation

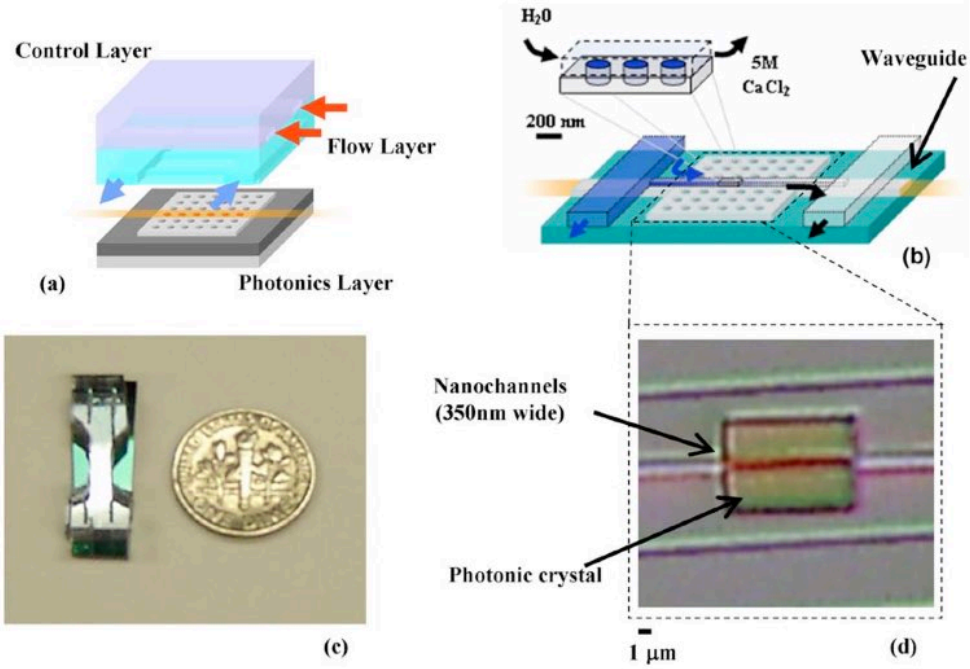
Topological structures

Liu Qiu's presentation

Microfluidics

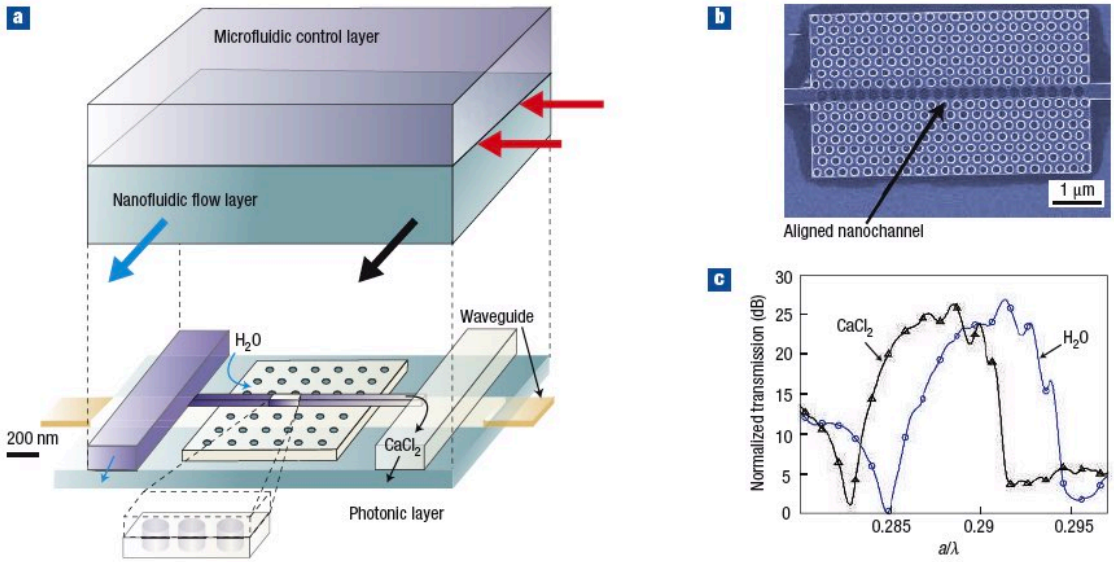
+ Rita Therisod's presentation

Hybridisation with other complex technologies



D. Erickson et al., Opt. Lett., 31, 59 (2006)

Microfluidics

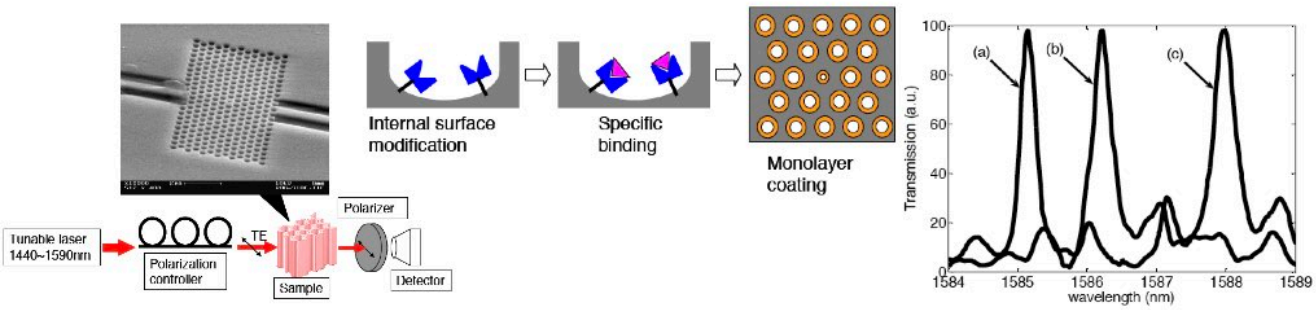


Review article C. Monat et al., Nat. Phot., 1, 106 (2007)

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

M. Lee et al., Opt. Exp., 15, 4530 (2007)

Slow light

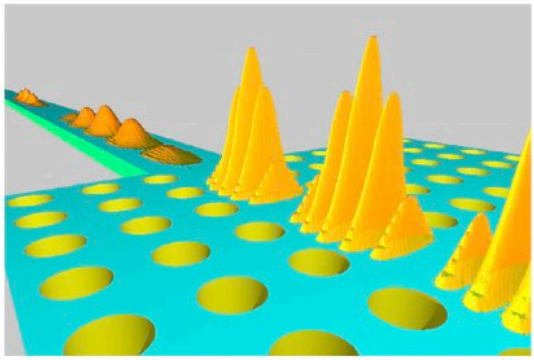
+ Morteza Navadeh's presentation

Motivation

- Enhancement of linear effects for a constant length $\propto n_g$
  - Delay line, buffer memory (≈ max a few 100 bits)
  - Commutation (for devices based on a Δk variation)
  - Sensors
- Polynomial enhancement of non-linear effects $\propto n_g^{\alpha}$
  - Diminution of the interaction length
  - Enhancement also due to intensity increase, $J = \rho . v_g$ if v_g ↘ then ρ ↗
- Quantum optics

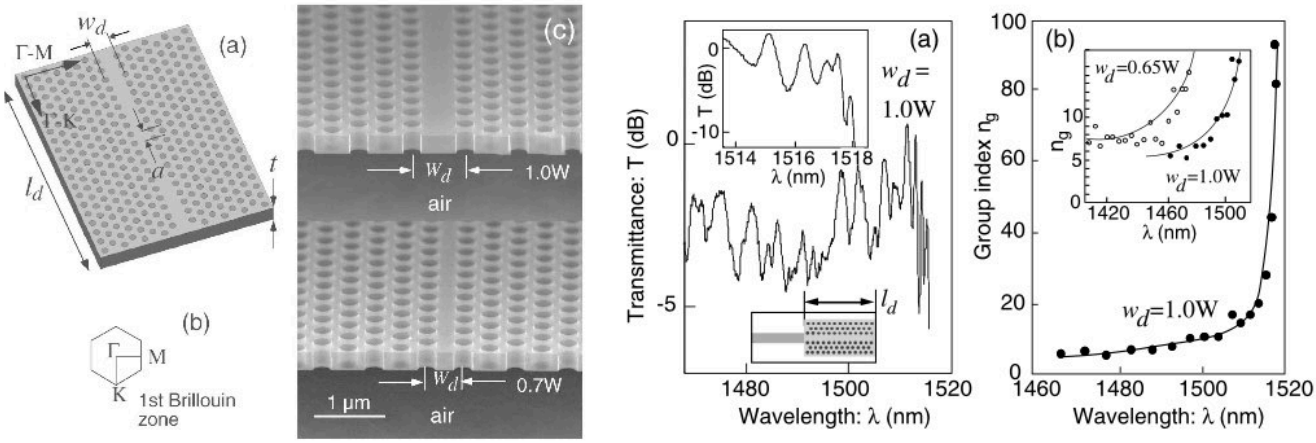
Issues

- Bandwidth
- Propagation losses
- Coupling
- Dispersion
- Disorder



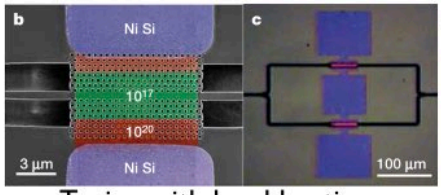
Review articles:
T.F. Krauss, J. Phys. D, 40, 2666 (2007)
T.F. Krauss, Nat. Phot., 2, 448 (2008)
T. Baba, Nat. Phot., 2, 465 (2008)

Slow light

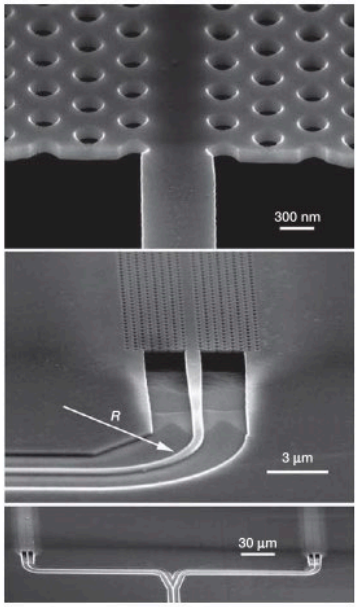


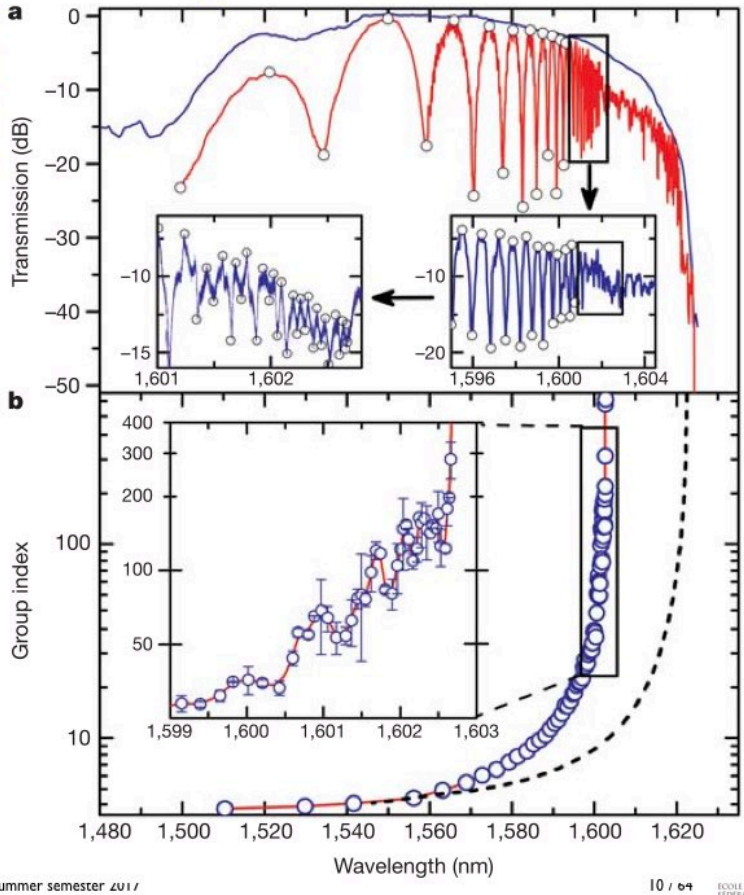
M. Notomi et al., Phys. Rev. Lett., 87, 253902 (2001)

Slow light



Tuning with local heating



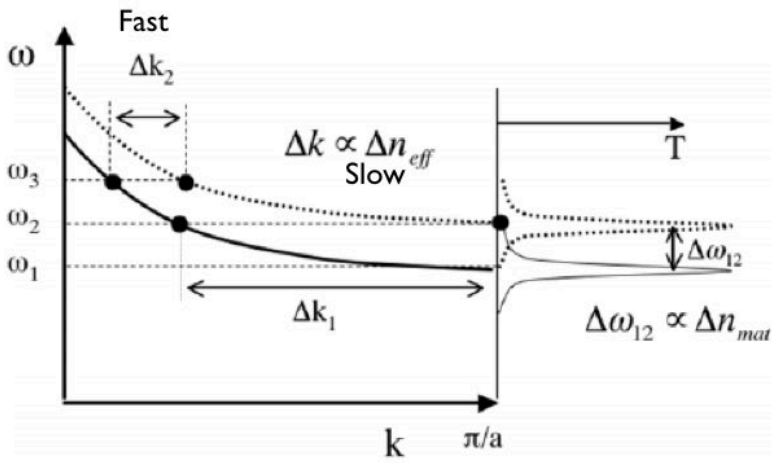


Y. Vlasov et al., Nature, 238, 65 (2005)

Slow light

Example of application in a Mach-Zehnder

- Commutation

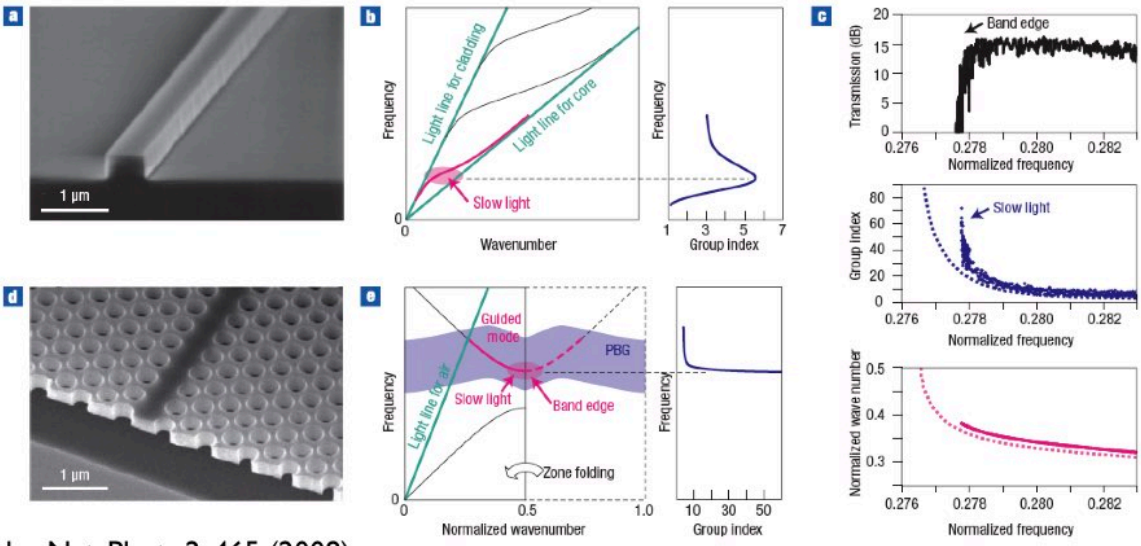


T.F. Krauss, J. Phys. D, 40, 2666 (2007)

Slow light

Some approaches

- Band edge
  - dispersion
  - losses
  - back reflection

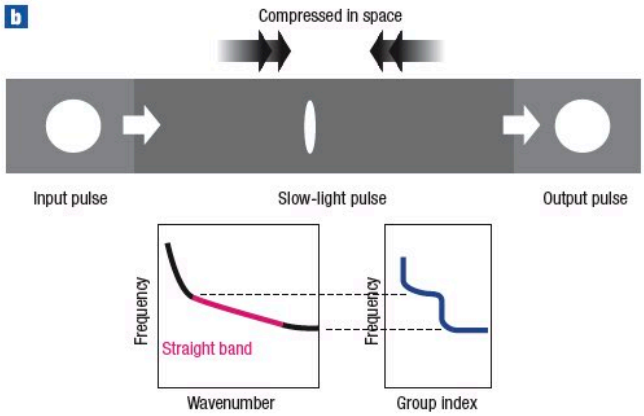


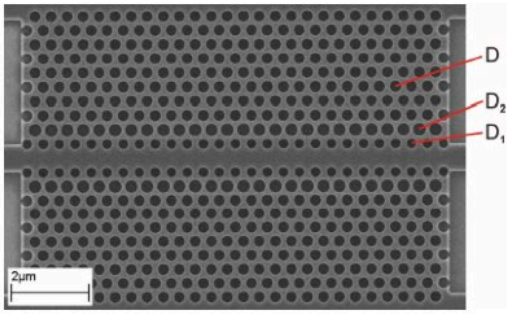
T. Baba, Nat. Phot., 2, 465 (2008)

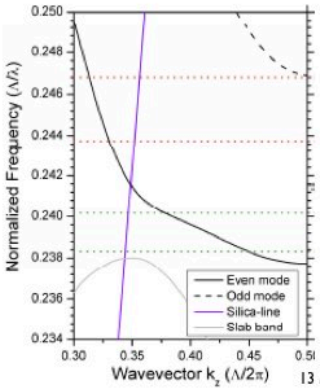
Slow light

Some approaches

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





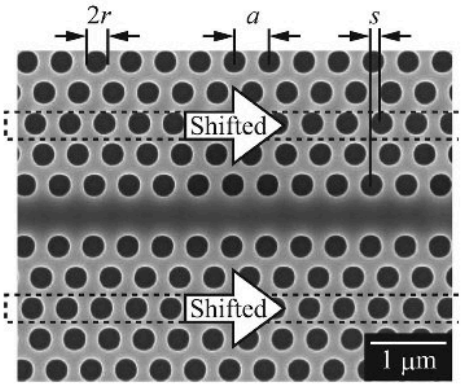


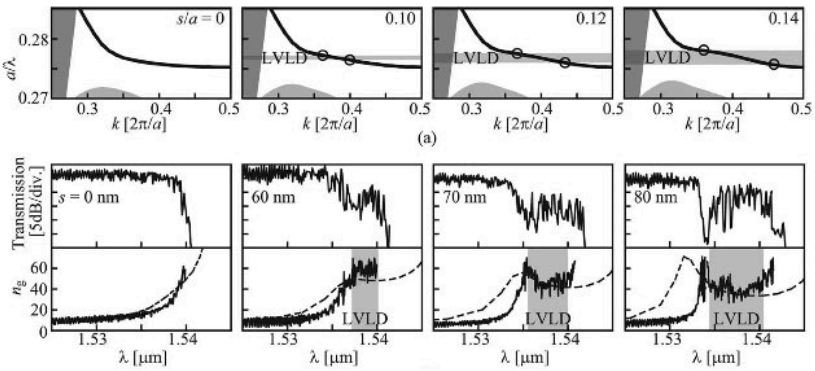
T. Baba, Nat. Phot., 2, 465 (2008)
L.H. Frandsen et al., Opt. Exp., 14, 9444 (2006)

Slow light

Some approaches

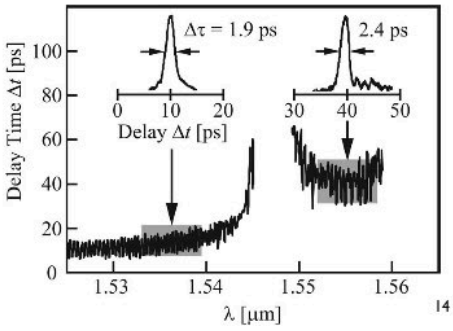
- Dispersion engineering





Shifted rows

$n_g \approx 30$
Low group velocity dispersion
Robustness

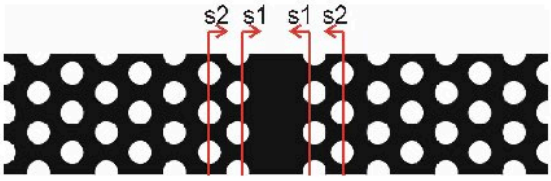


Y. Hamachi et al., Opt. Lett., 34, 1072 (2009)

Slow light

Some approaches

- Dispersion engineering



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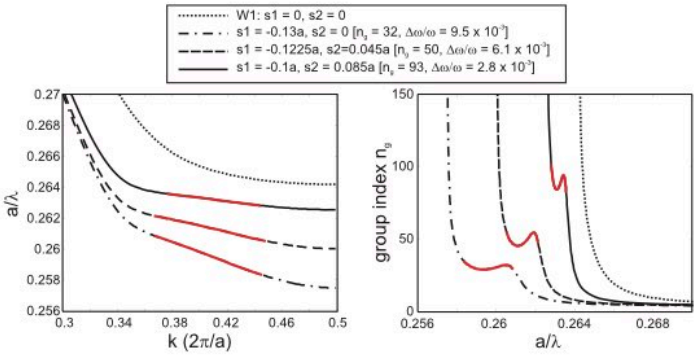
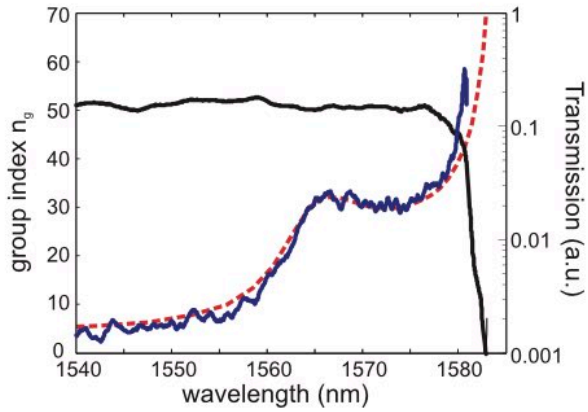




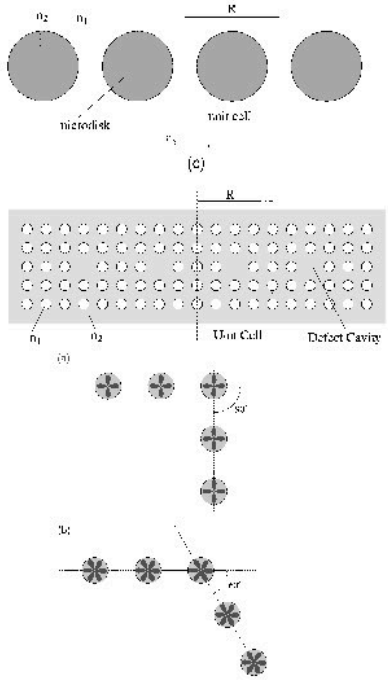
$n_g \approx 50$

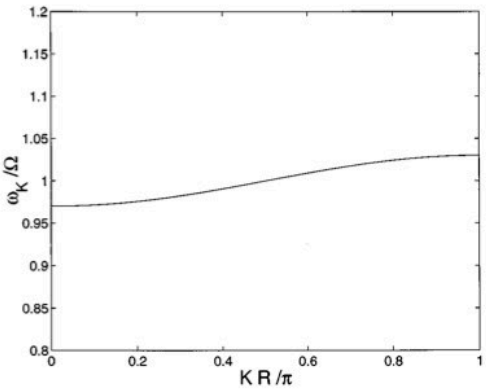
J. Li et al., Opt. Exp., 16, 6227 (2008)

Slow light

Some approaches

- Coupled cavities waveguides (CCW)





$$v_g(K) = \frac{\mathrm{d}\omega_K}{\mathrm{d}K} = -\Omega R \kappa_1 \sin(KR)$$

$$\omega_K = \Omega\left[1 - \frac{\Delta\alpha}{2} + \kappa_1 \cos(KR)\right]$$

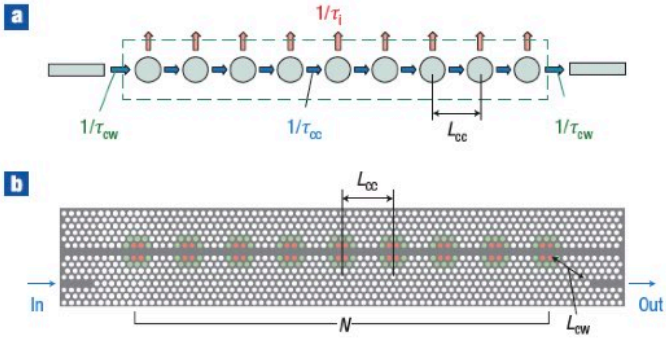
Coupling strength determines the dispersion curve (tight binding)

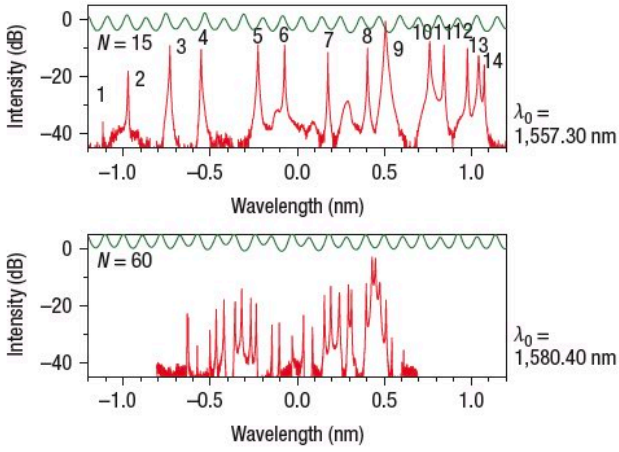
A. Yariv et al., Opt. Lett., 24, 711 (1999)

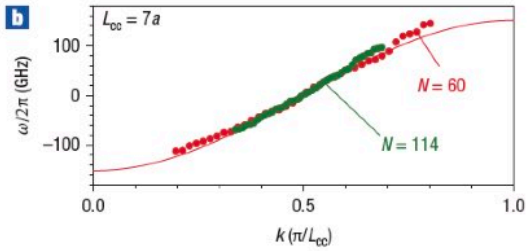
Slow light

Some approaches

- Coupled cavities waveguides (CCW)
- ▸ Transmission spectrum





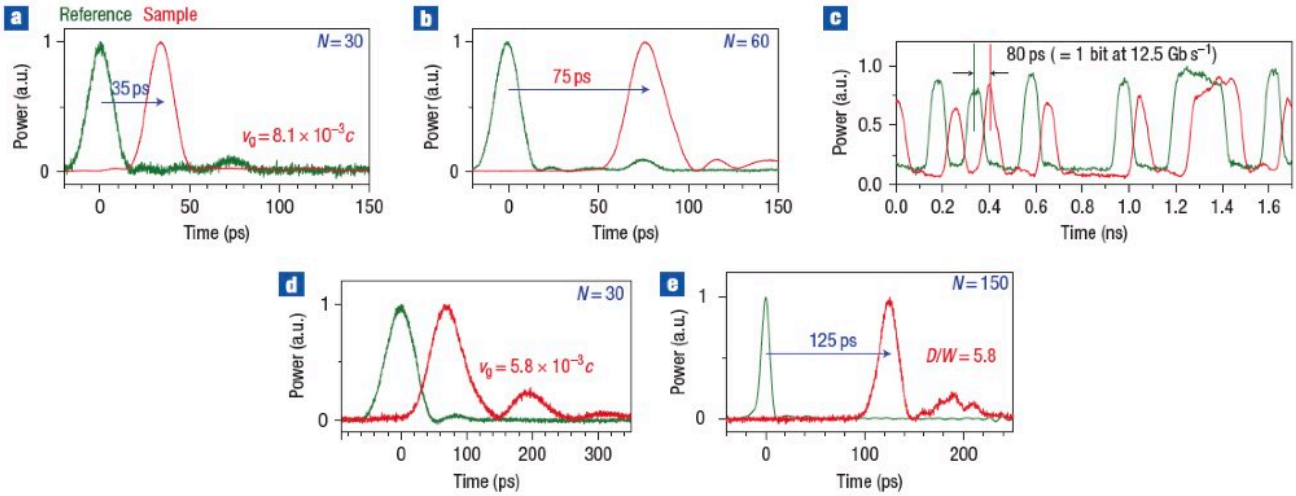


M. Notomi et al., Nat. Phot., 2, 741 (2008)

Slow light

Some approaches

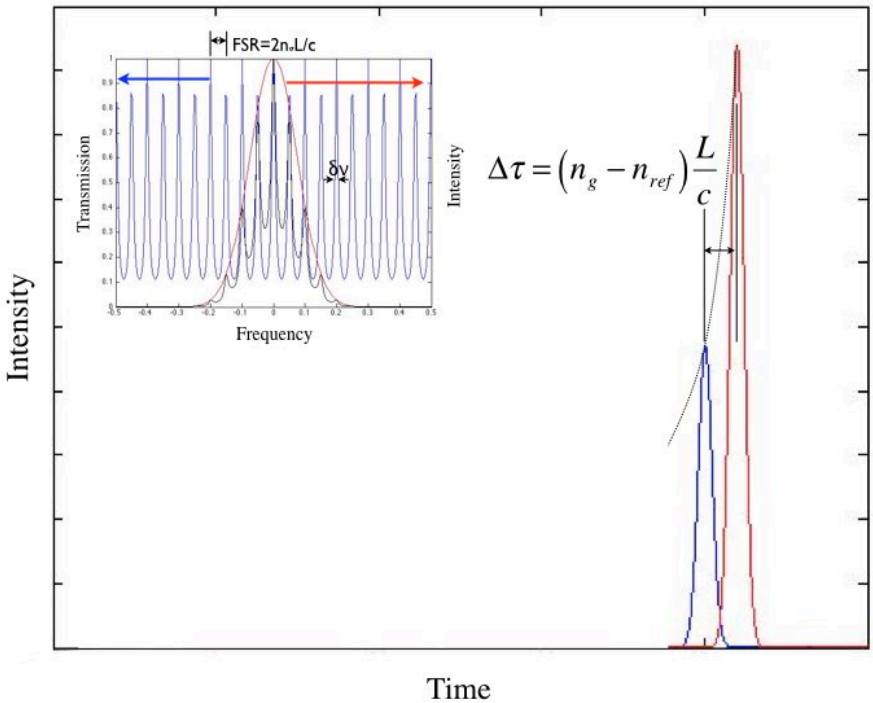
- Coupled cavities waveguides (CCW)
- ▸ Transmission spectrum



M. Notomi et al., Nat. Phot., 2, 741 (2008)

Slow light

Well sold, but … a flat transmission spectrum is mandatory

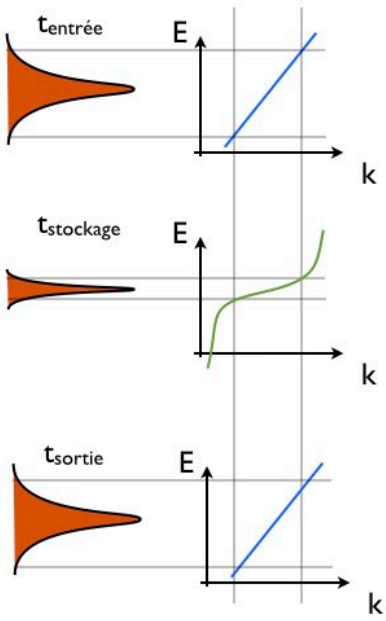


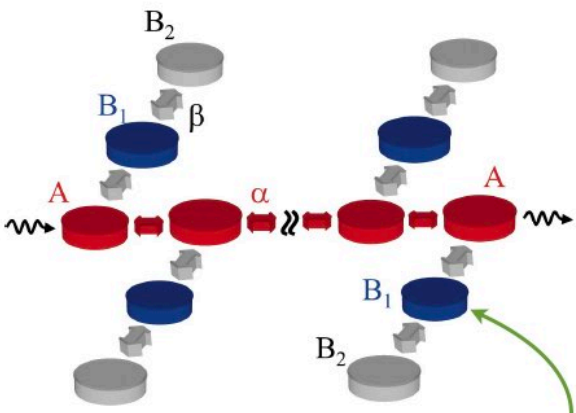
Echoes, cavity ring-down

Slow light

Some approaches

- Dynamic structures, see next sections





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

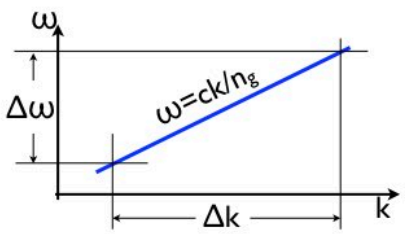
M.F. Yanik and S. Fan, Phys. Rev. Lett., 92, 083901 (2004)
M.F. Yanik and S. Fan, Phys. Rev. A, 71, 013803 (2005)

Slow light

Application	Figure of merit *F*	
• Single frequency	n_g	No universal figure
• Delay line	$n_g.\Delta u/u$	
• Buffering	$n_g.\Delta u/\lambda$	maximum number of bit per length that can be stored *provided the entire bandwidth is used*
• Non-linear effect	$n_g^{\beta}.\Delta u$	$\beta = 2, 3 \ldots$
• Spatial frequencies	$n_g.\Delta \check{k}$	*e.g.* small size ($1/\Delta k$) slow light laser
• Normalised delay	$n_g.\Delta u.L/a$	achievable delay in unit of pulse length
• Inclusion of losses	F/α ?	

Slow light

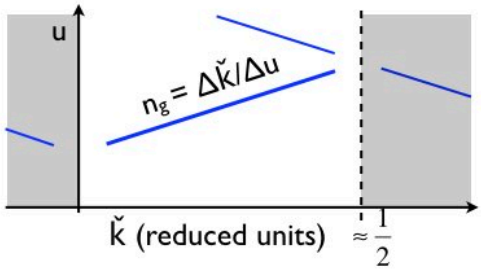
Intrinsic limits due to periodicity



Photonic crystal

⇒

Brillouin zone



$$\Delta k \leq \frac{\pi}{a} \quad \text{or} \quad \Delta\check{k} \leq \frac{1}{2} \qquad \boxed{n_g \frac{\Delta u}{u} \leq \frac{1}{2u} = \frac{\lambda}{2a}} \qquad \left(\text{or } \frac{\lambda}{2\Lambda} \text{ for a CCW, } \Lambda = Na\right)$$

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

Slow light

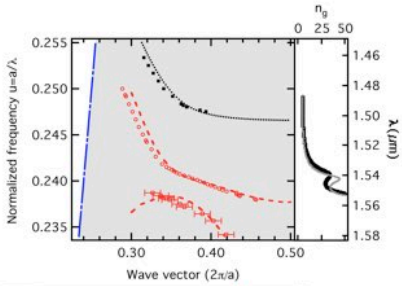
Intrinsic limits due to periodicity

$$n_g \frac{\Delta u}{u} \leq \frac{1}{2u} = \frac{\lambda}{2a} \approx 1.7 - 2$$

Current values :

Modified W1

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

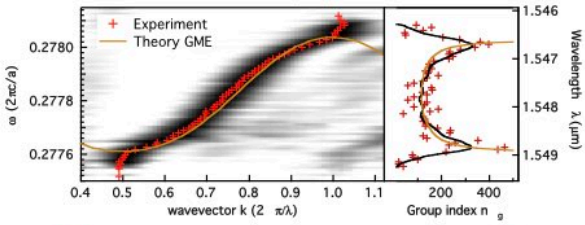


$n_g \Delta u/u = 0.25$

×10 margin for improvement

CCW

(e.g. J. Jágerská et al., Opt. Lett. 34, 359 2009)

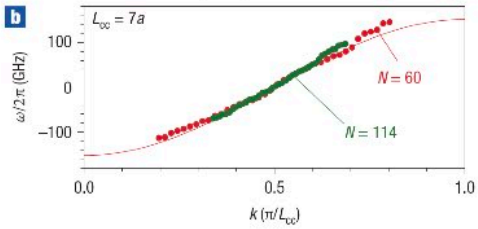


$n_g \Delta u/u = 0.18$

×2 margin for improvement close to the limit

CCW

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



$n_g \Delta u/u = 0.1$

Slow light

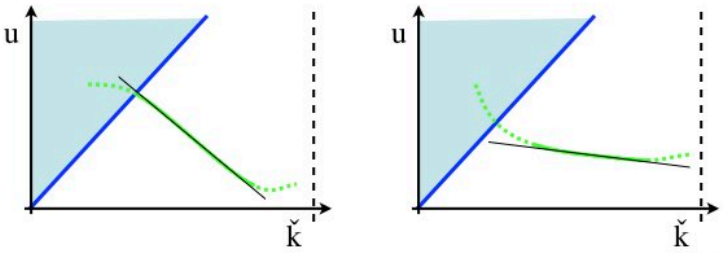
Intrinsic limits due to dispersion

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. $\Delta k_{scattering} \approx 1/l_{disorder}$
- Evanescent modes — Coupling, disorder

Desired :

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



Slow light

Extrinsic limits

- Residual disorder

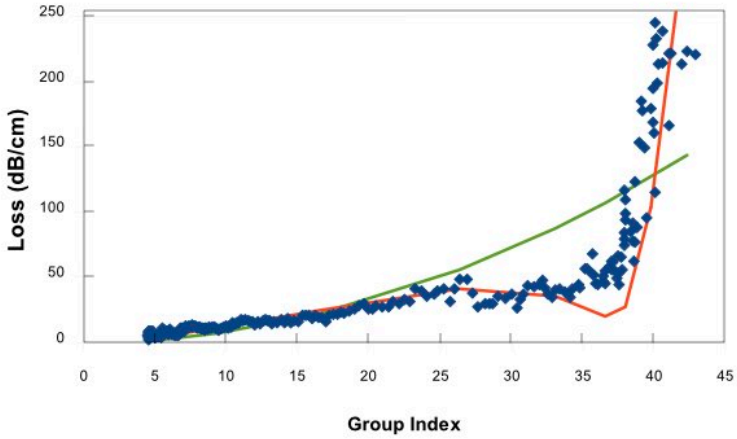
- Light-matter increased interaction due to slowing the light (*i.e.* increasing the density of states) applies also to interaction with defects such as disorder
- Disorder induced propagation losses $\propto n_g$ (linear response)
- Disorder induced back-scattering losses $\propto n_g^2$ (density of 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

- 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)

$\alpha = c_1 n_g + c_2 n_g^2$ + overlap and correlation terms $\alpha = c_1 \gamma(n_g) n_g + c_2 \rho(n_g) n_g^2$



Suggested authors to search in this field:

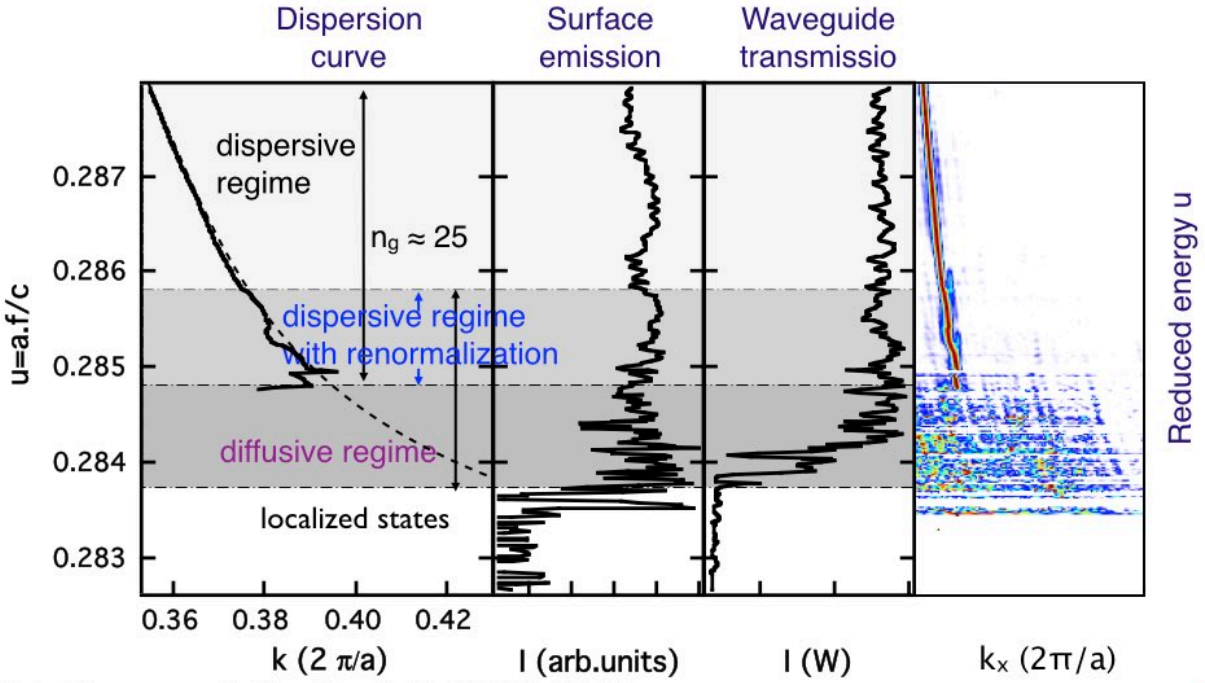
T. Krauss et al.	V. Savona
P. Lalanne et al.	L. Kuipers et al.
S. Hughes et al.	L.C. Andreani et al.
A. Melloni et al.	A. De Rossi et al.

L. O'Faolain et al., Opt. Exp. 18, 27627 (2010)

Slow light

Extrinsic limits

- For larger disorder/v_g, wavevector loses its relevance



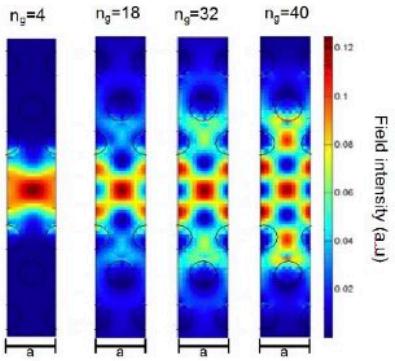
N. Le Thomas et al., Phys. Rev. B 80, 125332 (2009)

Slow light

Extrinsic limits

- Fast light / slow light transition

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



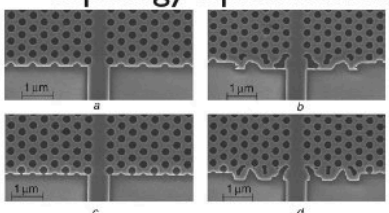
- High v_g, low v_g transition taper

N. Ozaki et al., Opt. Exp. 15, 7974 (2007).
J.P. Hugonin et al., Opt. Lett. 32, 2638 (2007).

- AR PhC intermediate layer

C.M. de Sterke et al., Opt. Exp. 15, 10984 (2007).

- Topology optimisation



5dB improvement but still -20dB

L. Yang et al., Electron. Lett. 43, 923 (2007).

Slow light

Extrinsic limits

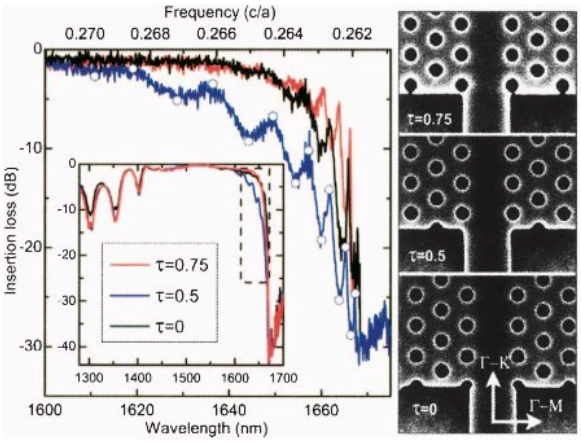
- Fast light / slow light transition

- Interplay with interface and evanescent modes

T.P. White et al., Opt. Lett. 33, 2644 (2008).

- Optimized hole termination, interplay with interface modes

Y.A. Vlasov and S.J. McNab, Opt. Lett. 31, 50 (2006).

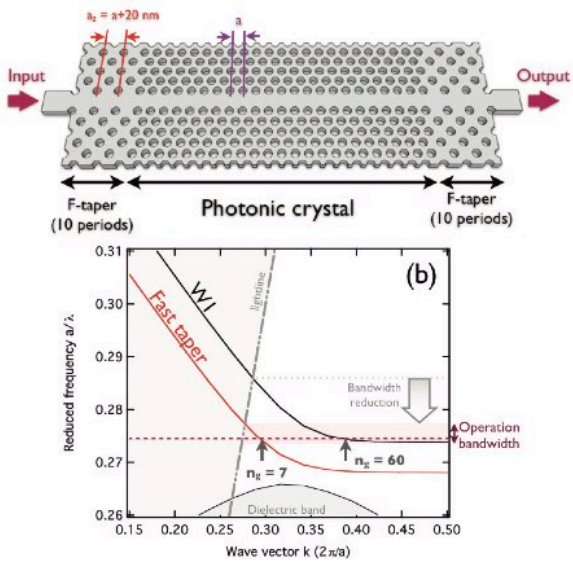


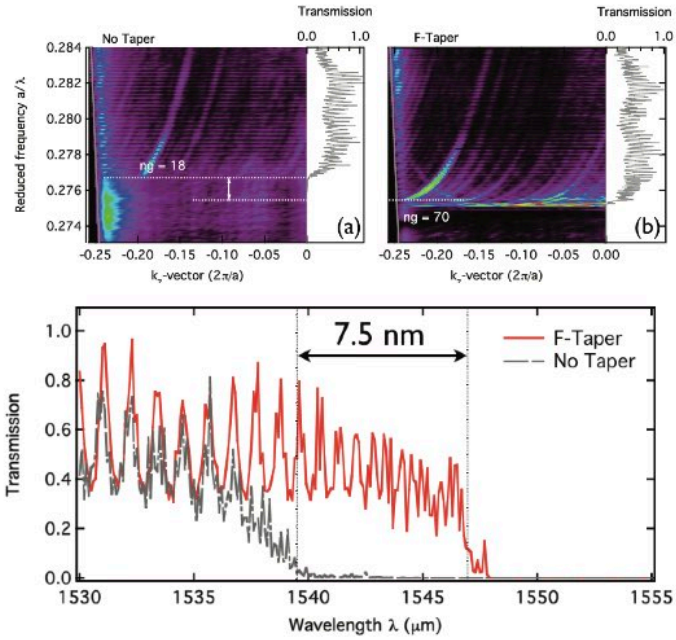
Slow light

Extrinsic limits

- Fast light / slow light transition

High v_g, low v_g transition taper





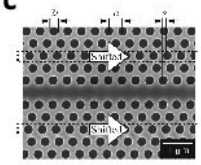
J. Jágerská, PhD dissertation, EPFL n°4956 (2010)

Slow light

State of the art

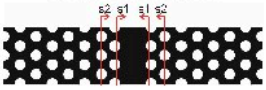
Many claims of very large n_g values (as large as 1000) are to be treated with great care !

$n_g \approx 30$



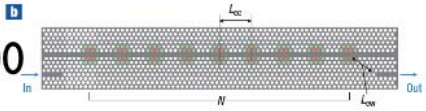
Y. Hamachi et al., Opt. Lett., 34, 1072 (2009)

$n_g \approx 50$



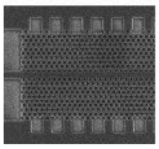
J. Li et al., Opt. Exp., 16, 6227 (2008)

$n_g \approx 100$



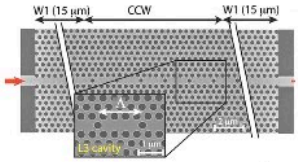
(CCW) M. Notomi et al., Nat. Phot., 2, 741 (2008)

$n_g \approx 30$



N. Le Thomas et al., Phys. Rev. B 76, 035103 (2007)

$n_g \approx 100$

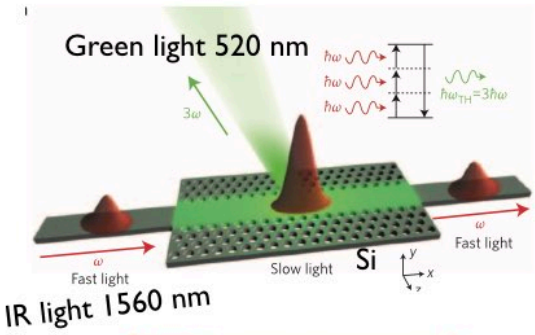


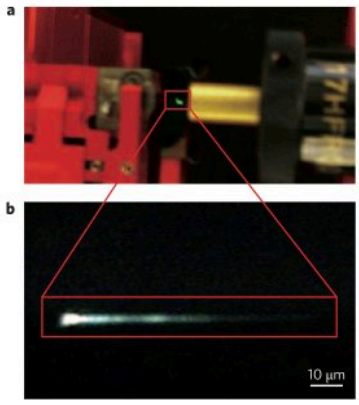
(CCW) J. Jágerská et al., App. Phys. Lett. 95, 111105 (2009)

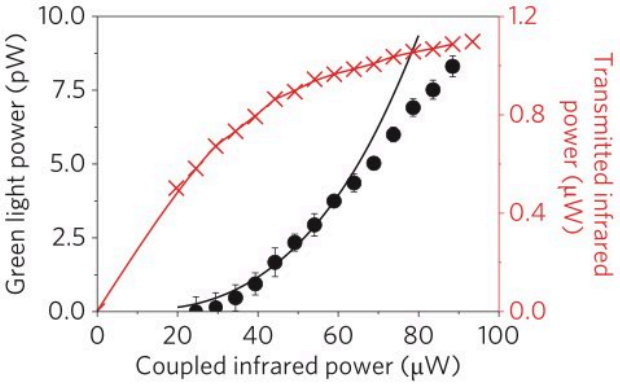
Review articles:
- T.F. Krauss, J. Phys. D, 40, 2666 (2007)
- T.F. Krauss, Nat. Phot., 2, 448 (2008)
- T. Baba, Nat. Phot., 2, 465 (2008)
- A. Talneau, J. Opt., 12, 104005 (2010)
- S.A. Schulz, J. Opt., 12, 104004 (2010)

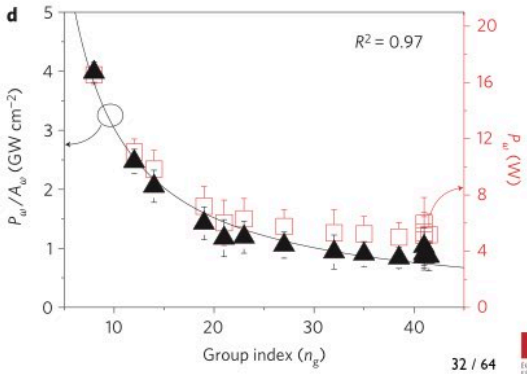
Slow light

Non linear effect, example : third harmonic generation





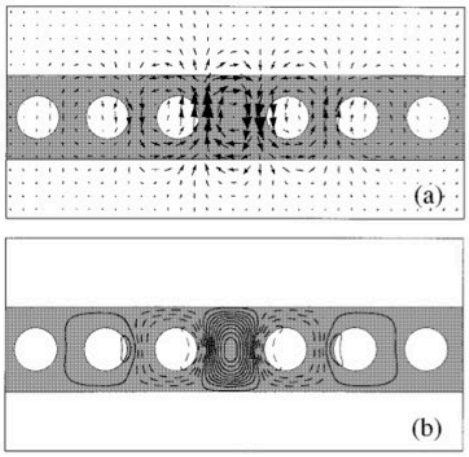




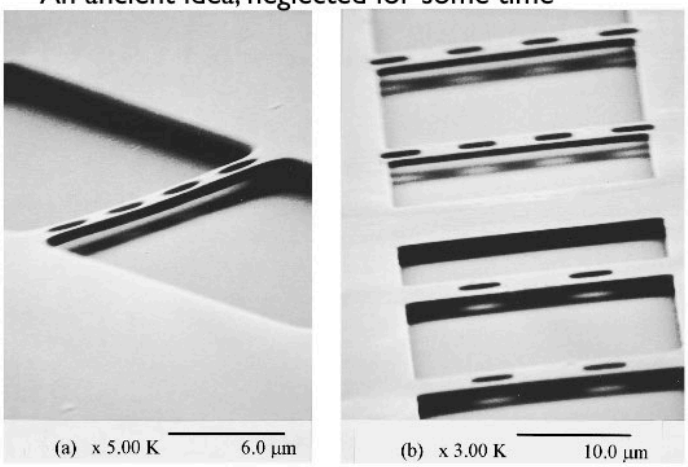
B. Corcoran et al., Nat. Phot., 3, 206 (2009)

Nanobeam

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



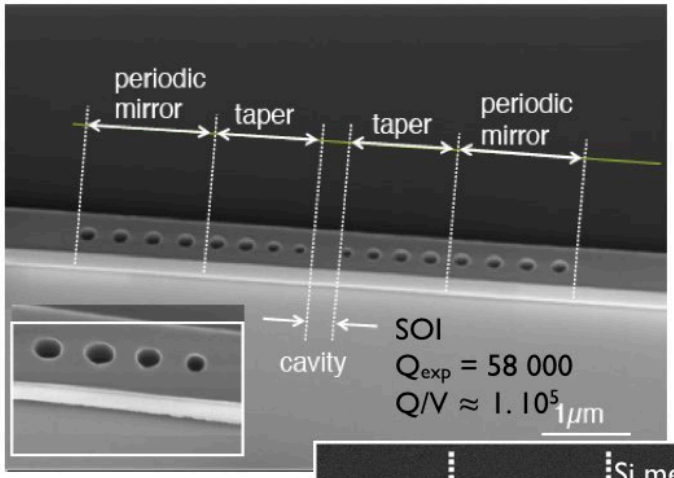
An ancient idea, neglected for some time

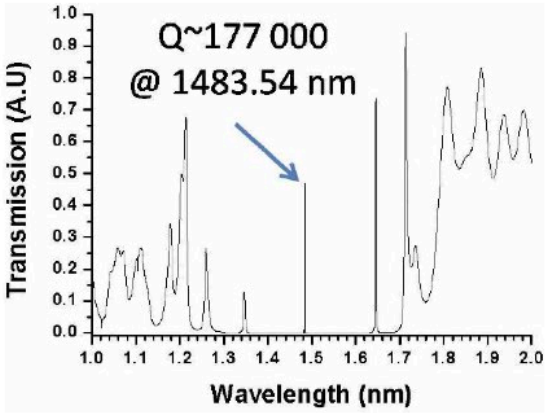


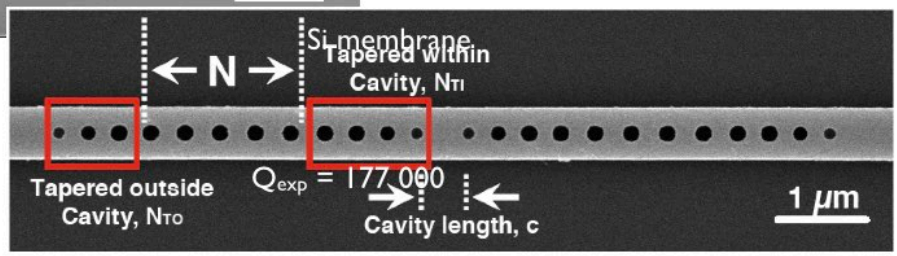
P. R. Villeneuve et al., App. Phys. Lett., 67, 167 (1995)

Nanobeam

P. Velha et al., Opt. Exp., 15, 16090 (2007)

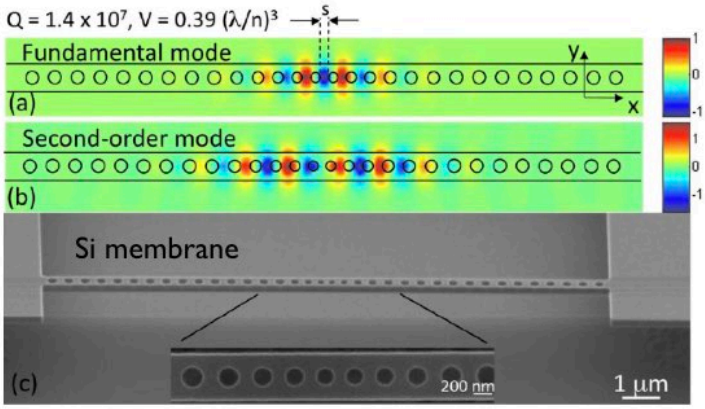






A. R. Md Zain et al., Opt. Exp., 16, 12084 (2008)

Nanobeam



P. B. Deotare et al., App. Phys. Lett., 94, 121106 (2009)

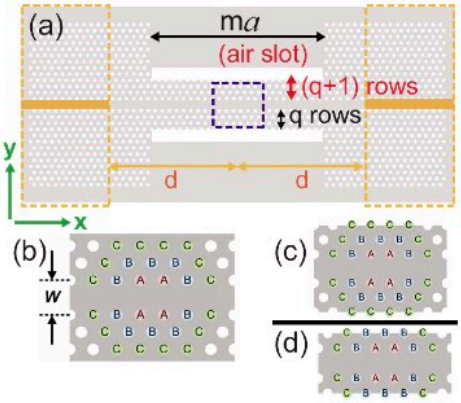
Q_{exp} = 750 000

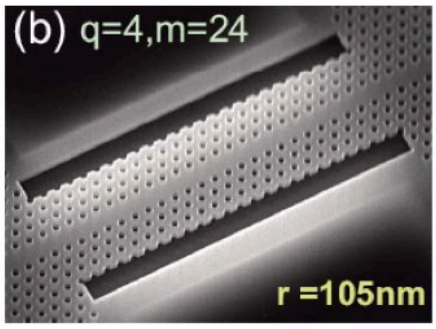
→ optomechanic systems

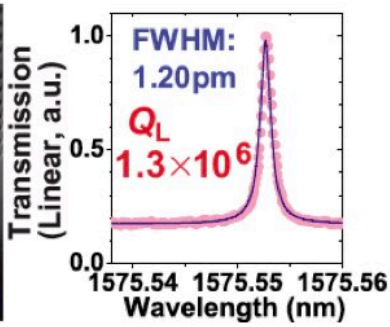
→ slotted guides

→ sensors

E. Kuramochi et al., App. Phys. Lett., 93, 111112 (2008)







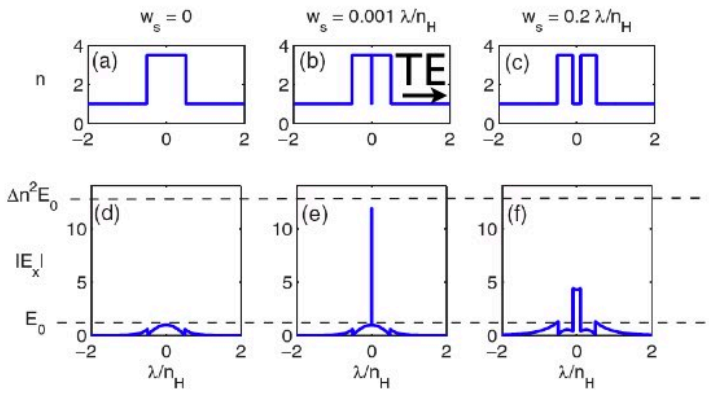
Slotted guides

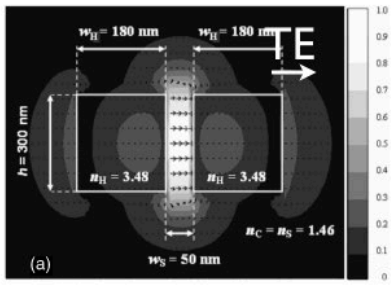
Guides with low index core / empty

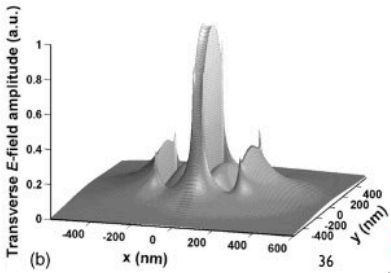
How to obtain guided mode in air

- 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



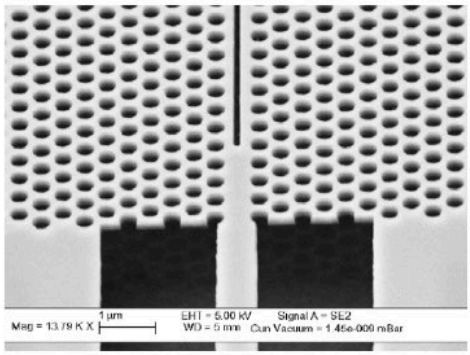


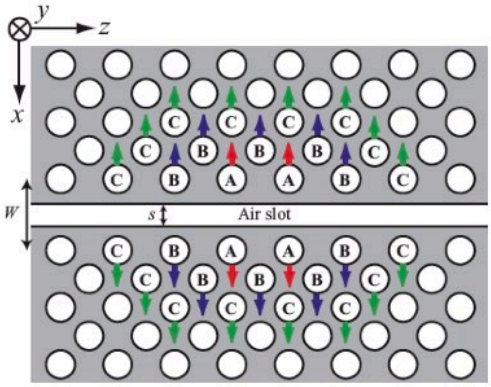


J.T. Robinson et al., Phys. Rev. Lett., 95, 143901 (2005)

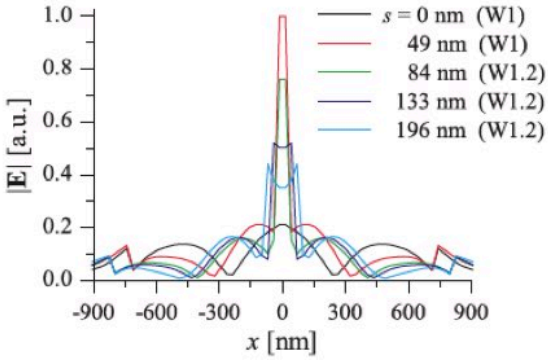
V.R. Almeida et al., Opt. Lett., 29, 1209 (2004)

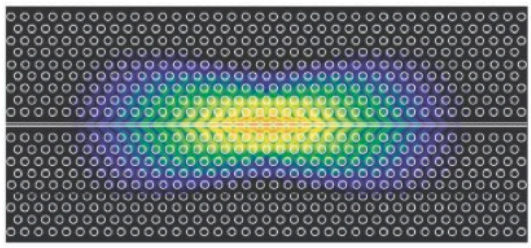
Slotted guides





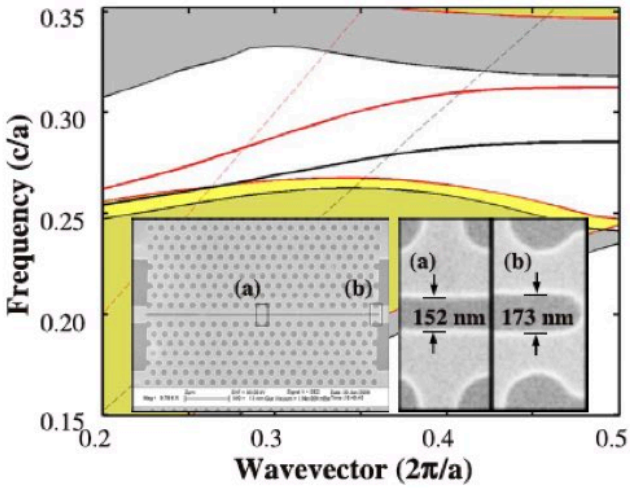
A. Di Falco et al., Phot. Nanostr., 6, 38 (2007)

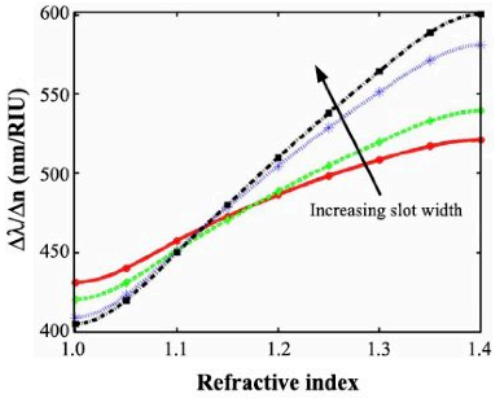


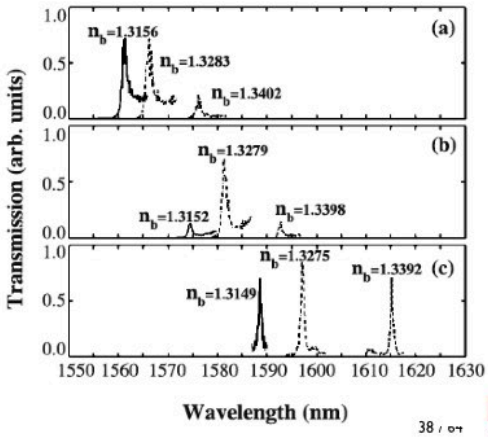


T. Yamamoto et al., Opt. Exp., 16, 13809 (2008)

Slotted guides / sensors





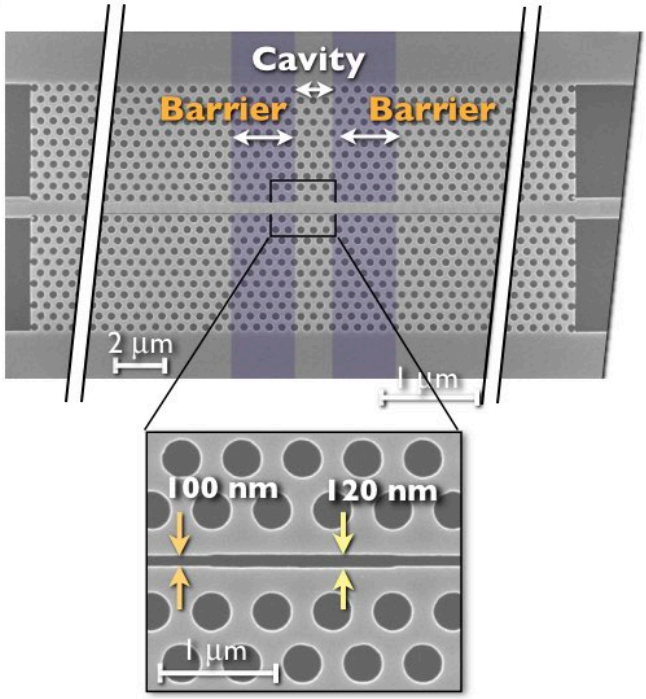


A. Di Falco et al., Appl. Phys. Lett., 94, 063503 (2009)

Slotted guides / sensors

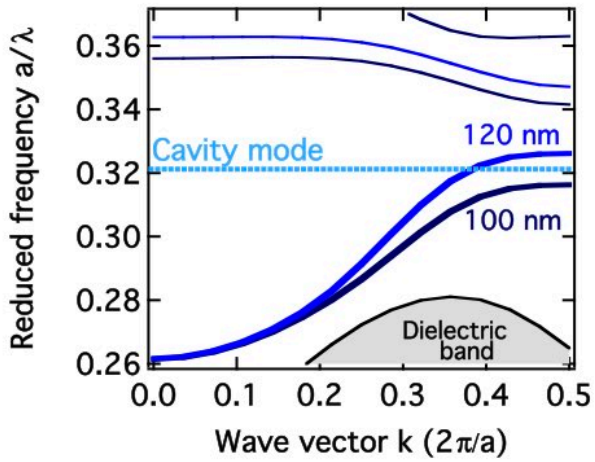
Slotted W1 waveguide
a = 510 nm, f = 0.36, s = 120 nm

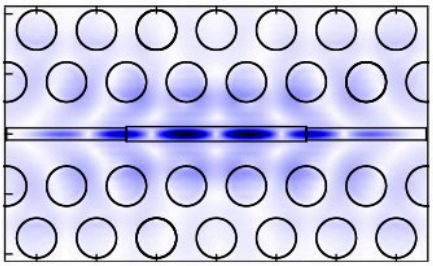
Cavity:
Slot 100-120-100 nm
3a cavity, 5a barrier



J. Jágerská. et al., Opt. Lett., 25, 2523 (2010)

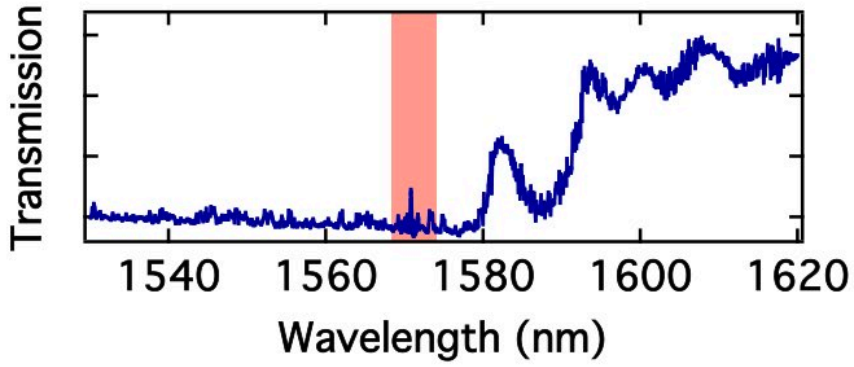
Slotted guides / sensors

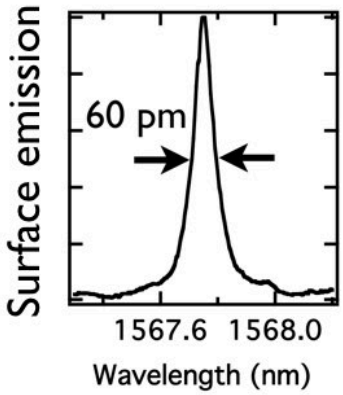




J. Jágerská. et al., Opt. Lett., 25, 2523 (2010)

Slotted guides / sensors



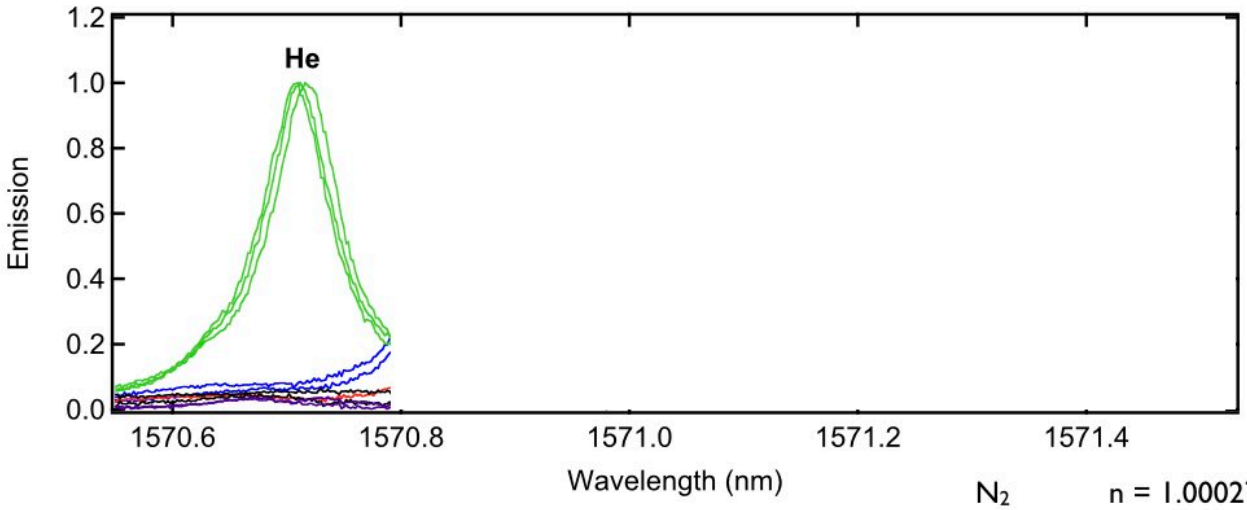


Quality factor
Q = 26 000

J. Jágerská. et al., Opt. Lett., 25, 2523 (2010)

Slotted guides / sensors

Wavelength shift of the cavity resonance upon exposure to gasses



40 attolitter = 0.04 μm^3
= 1.8 attomol
= 7.2 attogram (He)
≈ 10^6 molecules

Sensitivity = 610 nm/RIU

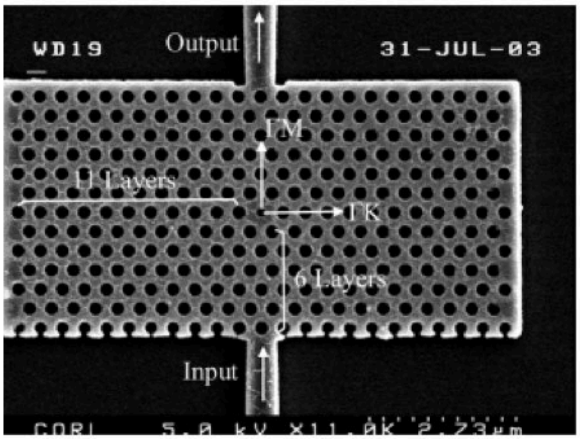
N_2	n = 1.000270
He	n = 1.000032
CO_2	n = 1.000406
C_2H_2	n = 1.000579
C_3H_8	n = 1.000999

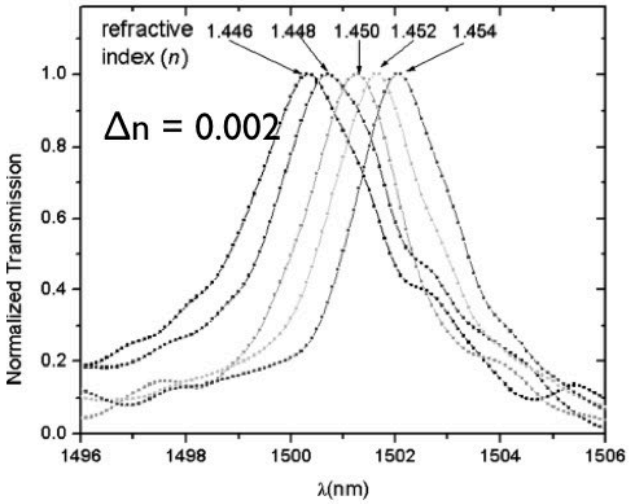
J. Jágerská. et al., Opt. Lett., 25, 2523 (2010)

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

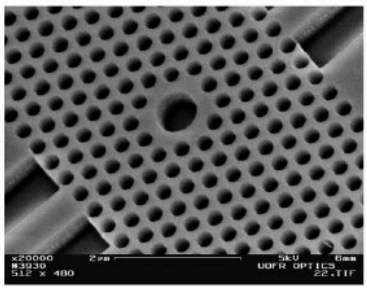




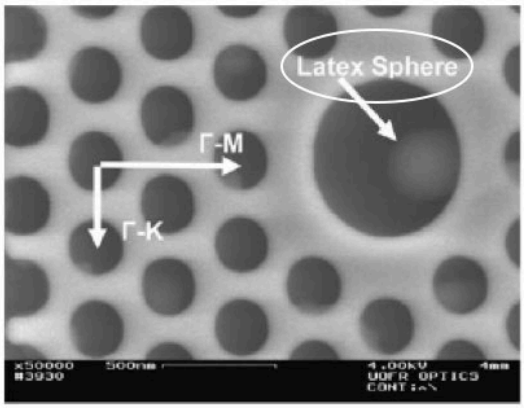
E. Chow et al., Opt. Lett., 29, 1093 (2004)

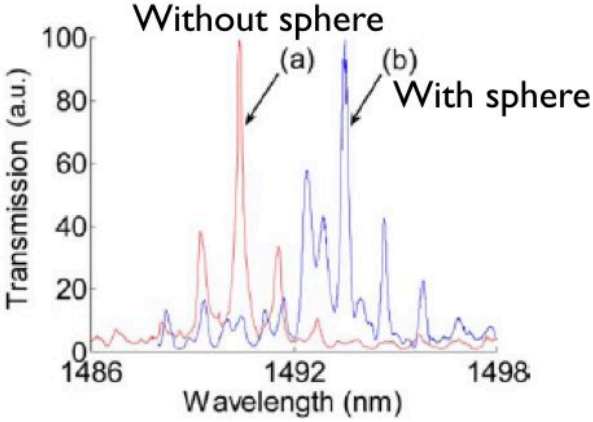
Sensors

A little bit more elaborated
V = 0.15 μm³ / 1 fg



Final goal : functionalize the sphere surface

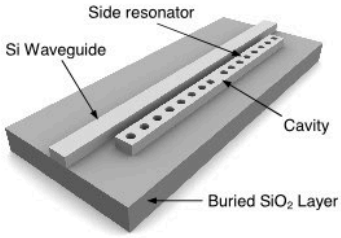


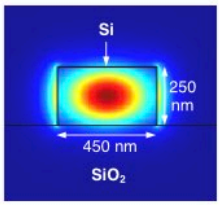


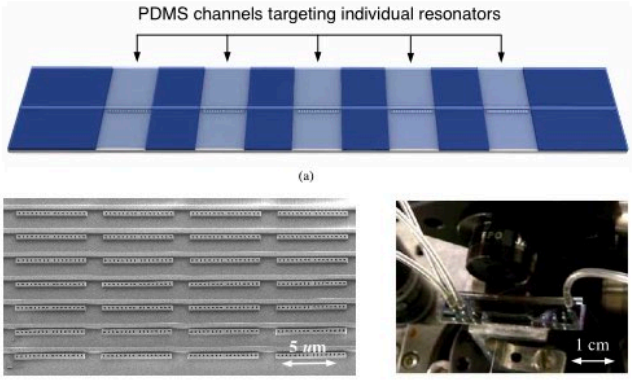
M. R. Lee et al., Opt. Lett., 32, 3284 (2007)

Sensors

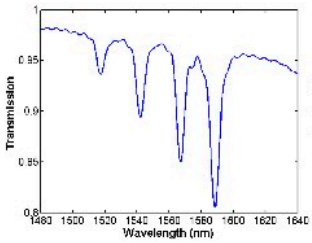
Integrated in a µfluidics environment

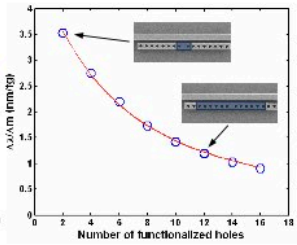


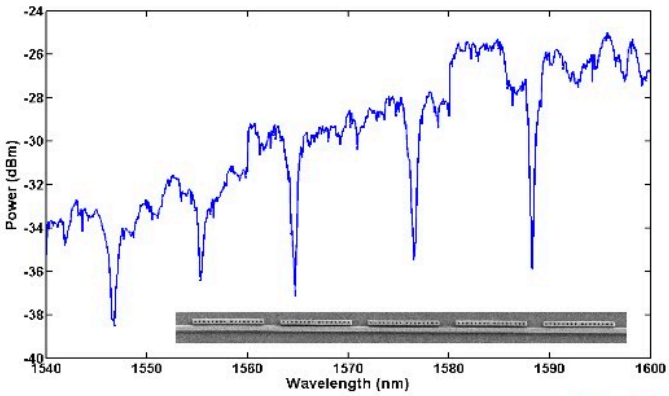




Functionnalized holes
Label free
Refractive index detection limit 7.10^{-5}
10 attograms



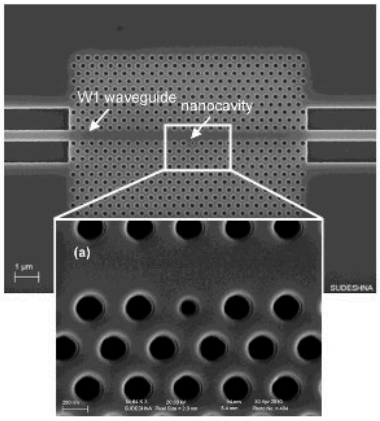


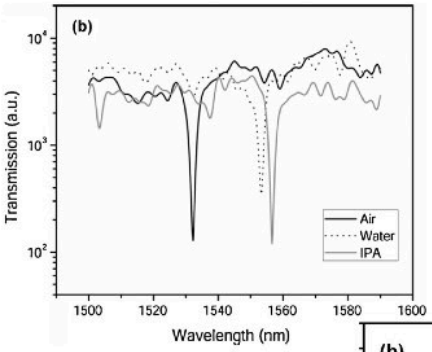


S. Mandal et al., Opt. Exp., 16, 1623 (2008)

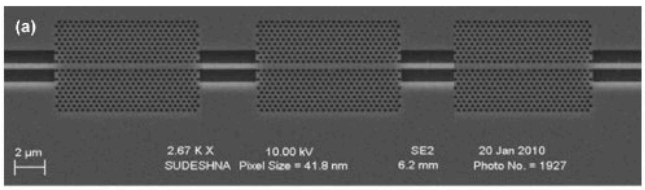
Sensors

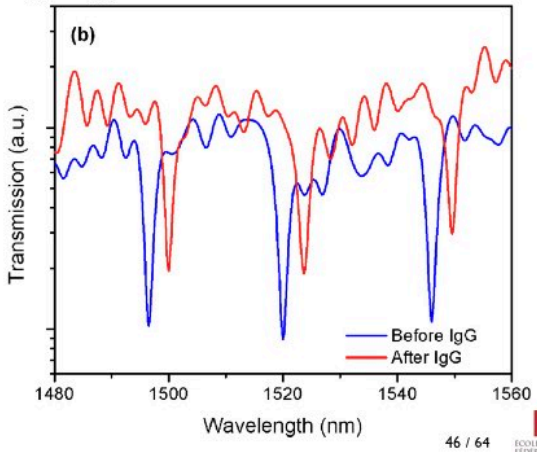
Integrated in a µfluidics environment





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



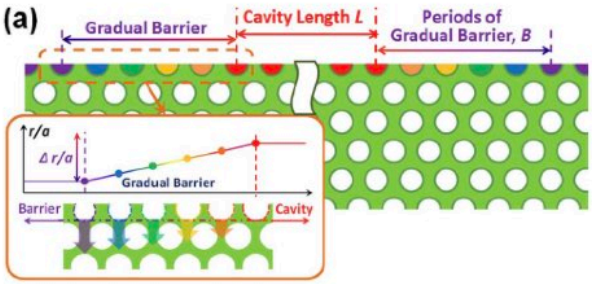


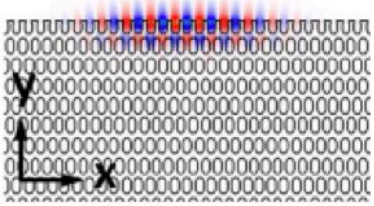
S. Pal et al., Biosensors Bioelec., 26, 4024 (2011)

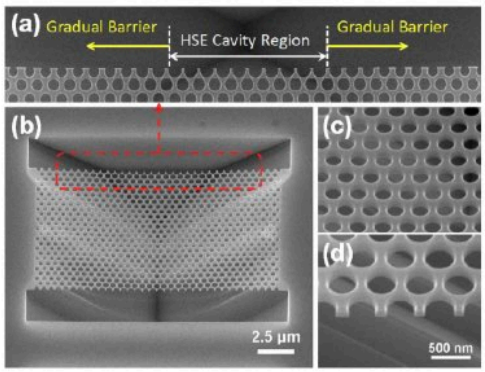
Sensors

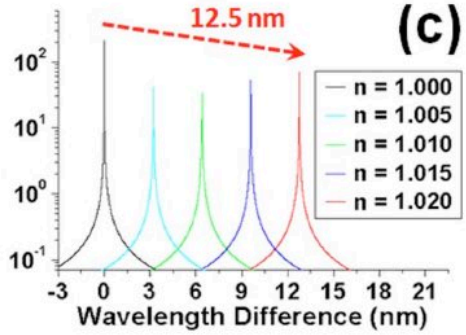
A more original approach to obtain optical field in air

- Heterostructure cavity
- Surface mode + open holes
- Measurement $\lambda_{laser}(n)$
- 625 nm/RIU or $\Delta n = 3.6.10^{-6}$ (modelling)









Modelling

T.S. Lu et al., Appl. Phys. Lett., 94, 141110 (2009)

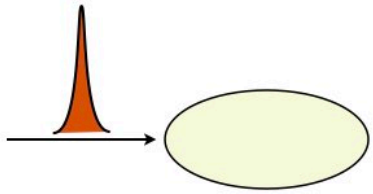
Dynamic control

+ Antoine Delgoffe's presentation

Control in time of the optical properties of the structure

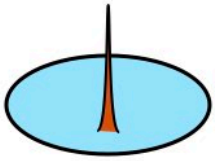
Example : quality factor of a cavity

t_{input}



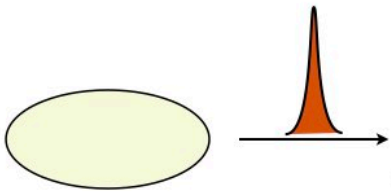
Low Q, in-coupling fast and efficient

$t_{storage}$



High Q, long ligetime of the pulse in the cavity

$t_{readout}$



Low Q, out-coupling fast and efficient

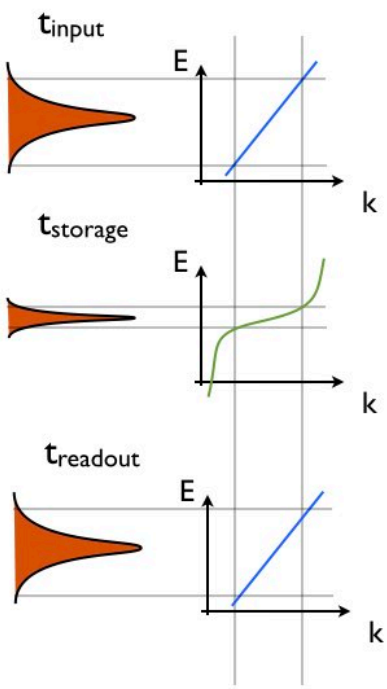
Dynamic control

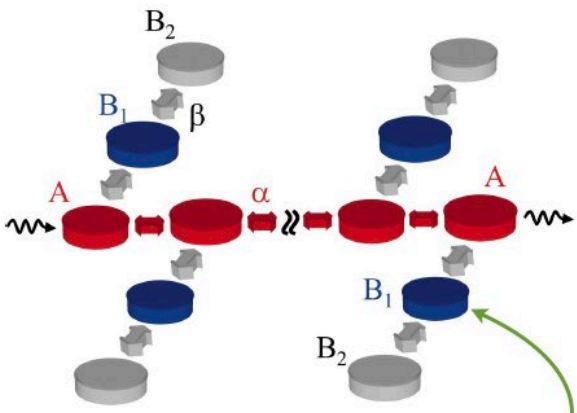
Control in time of the optical properties of the structure

Other more advanced applications :

Translational invariance	⇒	k conservation		
Structure non translational invariant	⇒	No k conservation	⇒	Chirped structures
Time invariant structure	⇒	Energy conservation		
Time dependant structure	⇒	No energy conservation	⇒	Dynamic control

Dynamic control

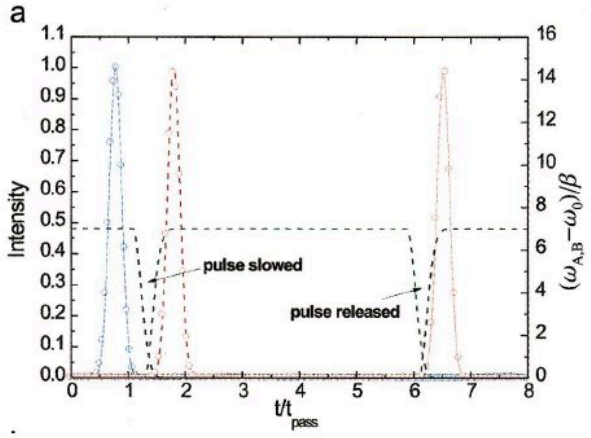


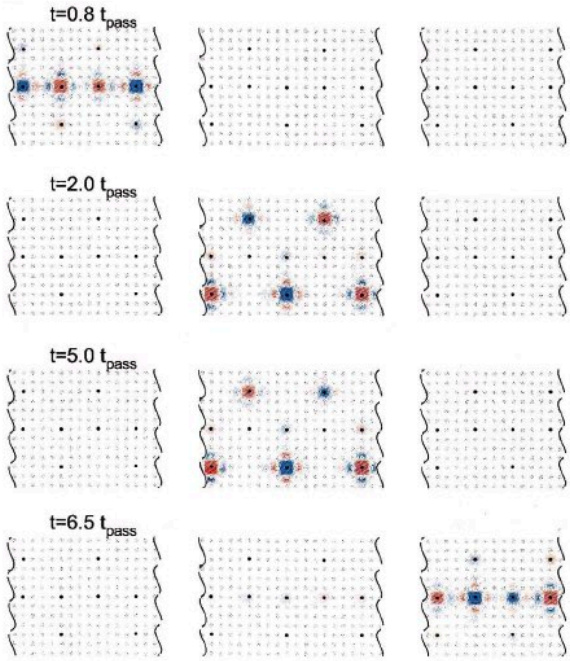


Commutation between fast and slow regime is achieved in changing the coupling constant

M.F.Yanik and S. Fan, Phys. Rev. Lett., 92, 083901 (2004)
M.F.Yanik and S. Fan, Phys. Rev. A, 71, 013803 (2005)

Dynamic control



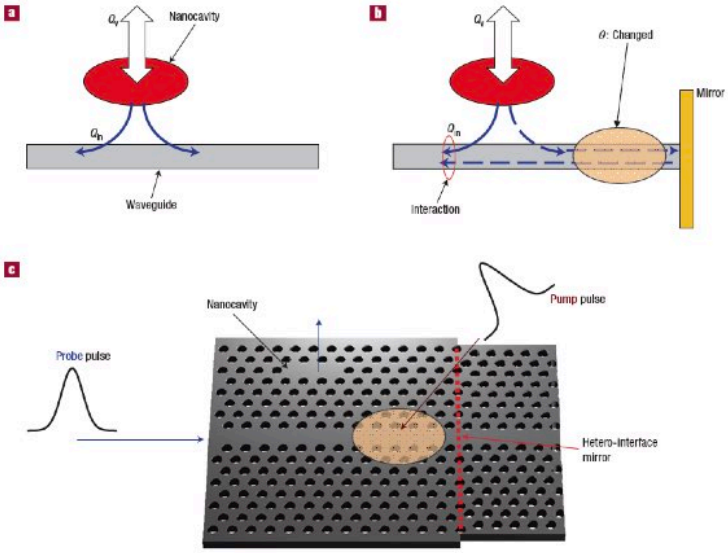


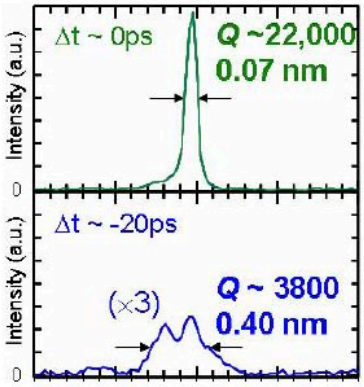
Only modelling

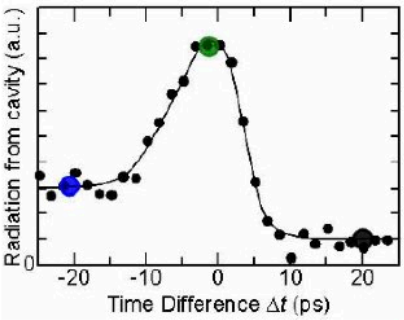
M.F. Yanik and S. Fan, Phys. Rev. Lett., 92, 083901 (2004)
M.F. Yanik and S. Fan, Phys. Rev. A, 71, 013803 (2005)

Dynamic control

Dynamic control of the quality factor of a cavity



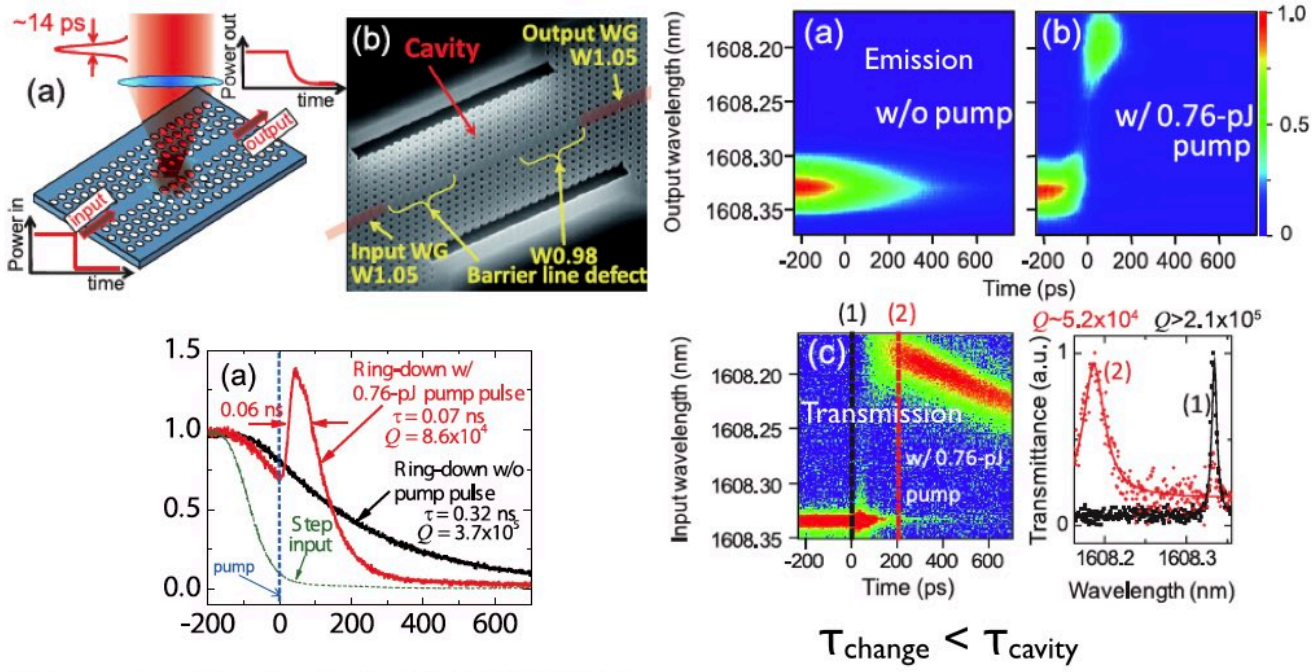




Y. Tanaka, Nat. Mat., 6, 862 (2007)
J. Upham et al., Opt. Exp., 16, 21721 (2008)

Dynamic control

Trap and release of a pulse and frequency shift



$T_{change} < T_{cavity}$

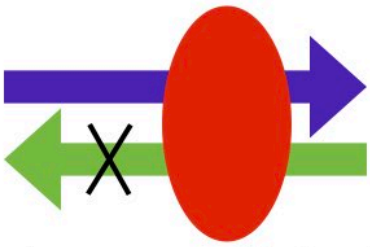
T. Tanabe et al., Phys. Rev. Lett., 102, 043907 (2009)

Non-reciprocal systems

+ Liu Qiu's presentation

Very active topic also in the metamaterials field

Needed functionality in many optical systems



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

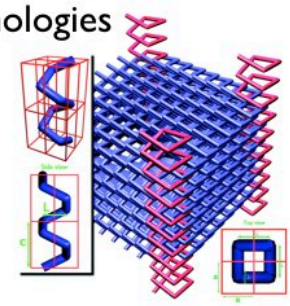
Require systems with time invariance symmetry breaking (t → -t) or time-dependent structures

- Magneto-optical materials
- Non-linear effects
- Non centro-symmetric structures
  - chiral structures (metamaterials)

Little compatibility with integrated optics technologies

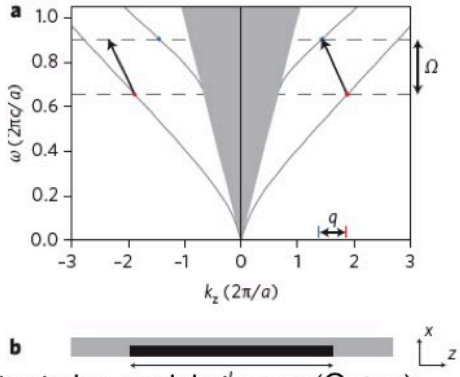
Imperfect

Imperfect

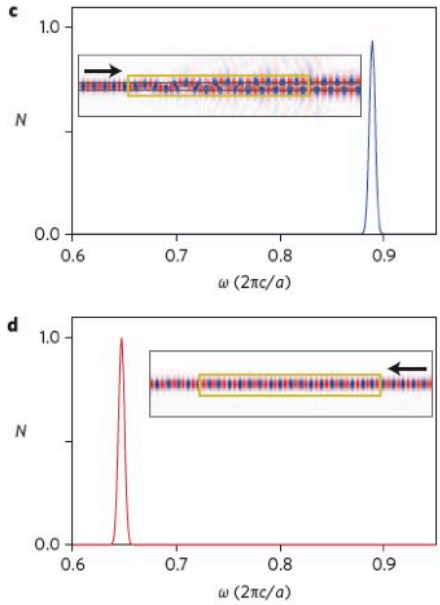


Non-reciprocal systems

Oblique transitions with breaking of
- translational invariance Δk
- 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

Z. Yu and S. Fan, Nat. Phot., 3, 91 (2009)

Non-reciprocal systems

$L = 2L_c$

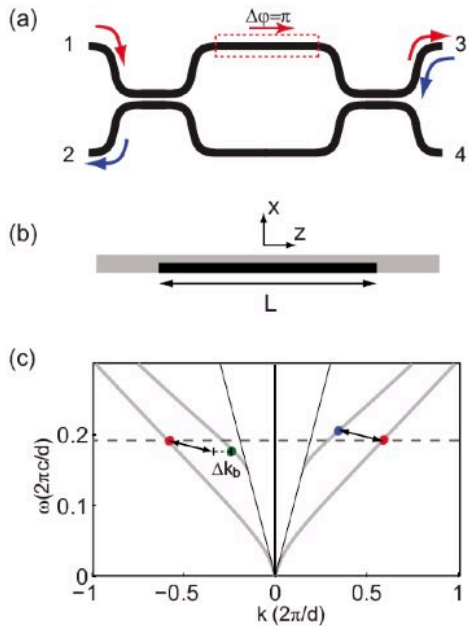
$\omega_1 \rightarrow \omega_2 \rightarrow \omega_1$

$\omega_1 \leftarrow \omega_1 \leftarrow \omega_1$

Purpose is to introduce a non-reciprocal π phase shift

port 1 → port 3

port 2 ← port 3



Z. Yu and S. Fan, Appl. Phys. Lett., 94, 171116 (2009)

Novel materials

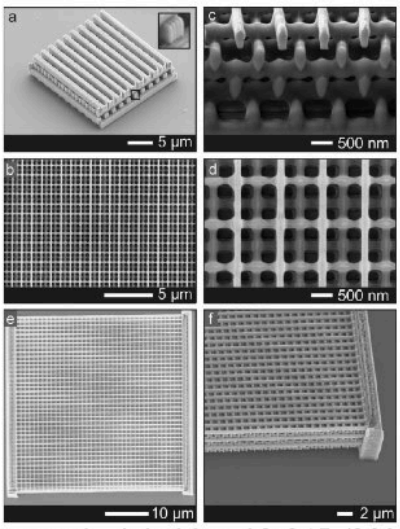
- Chalcogenides
- SiC
- Diamond
- GaP
- GaN and III-N
- Deformable structures

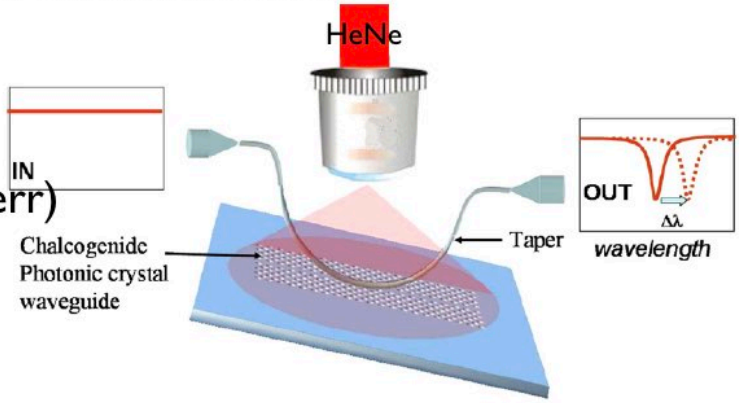
  Nicola Bartolomei's presentation

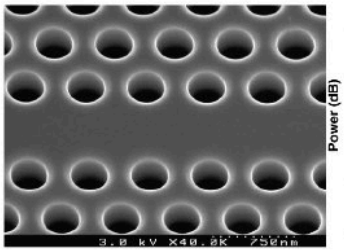
Chalcogenides

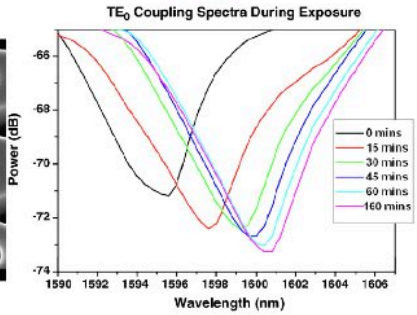
Photorefractif, photo-induced metastables states

- Fabrication
- Trimming
- $\Delta n \approx 2{,}5$
- Fast non-linear effets (Kerr)





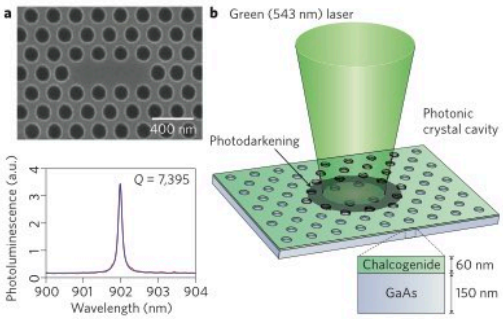


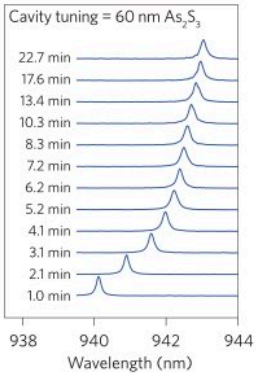


S. Wong et al., Adv. Mat., 18, 265 (2006) D. Freeman et al., Phot. Nanost., 6, 3 (2008)

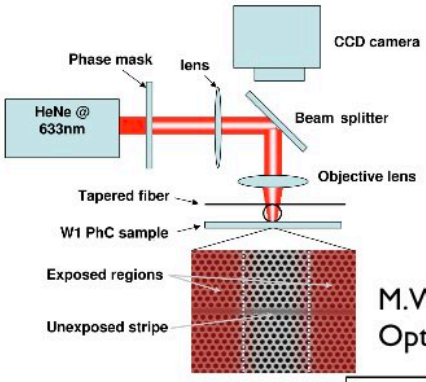
Chalcogenides

Tuning

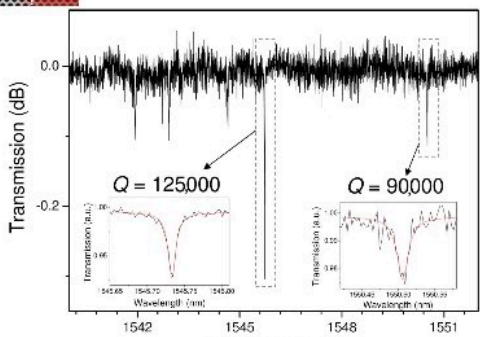




Photowritten high-Q cavities



M.W. Lee et al., Opt. Lett., 34, 3671 (2009)



Review on Chalcogenide photonics : N. Eggleton et al., Nat. Phot., 5, 141 (2011)

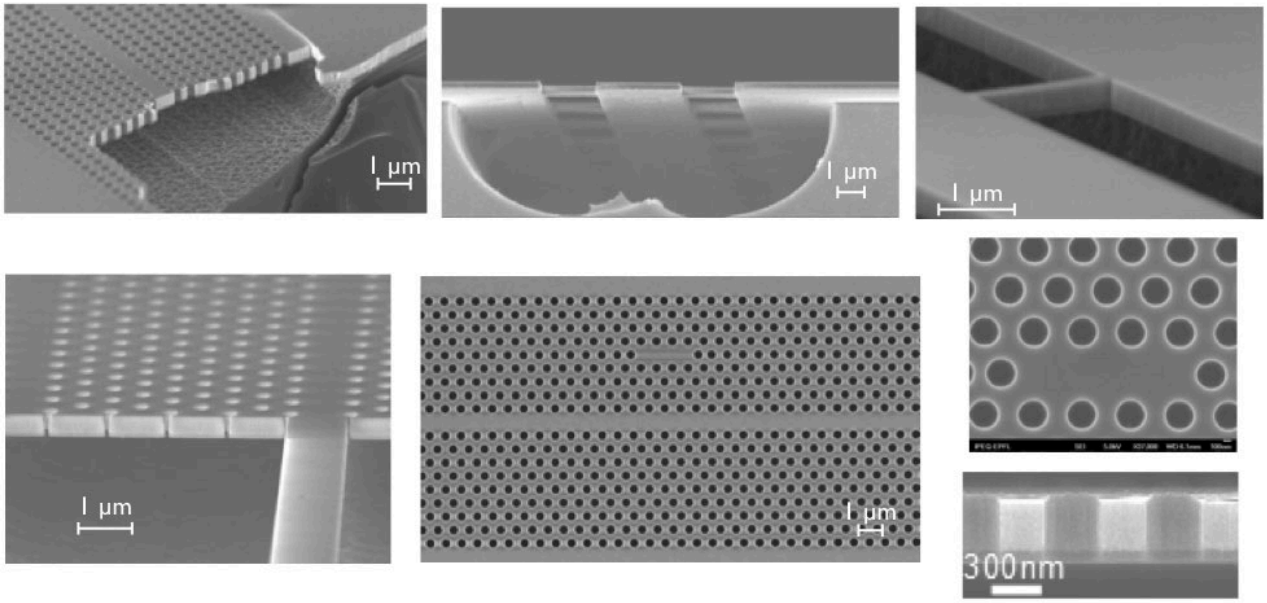
GaN and III-N

Large bandgap material PhC, possible materials

Material	Refractive index	Band gap
GaN	2.6 @ 370 nm 2.4 @ 500 nm 2.39 @ 600 nm	3.4 eV
AlN	2.17 @ 500 nm	6.2 eV
SiN_x	≈ 2.0	3–4 eV
SiC	2.5-2.8	2.4–3.6 eV
SiO_2	≈1.45	
ZnO	1.8–2.34	3.3 eV
GaP	3.25–3.44	2.2 eV
Diamond	2.37-2.67	5.5 eV

GaN and III-N

Suspended structures



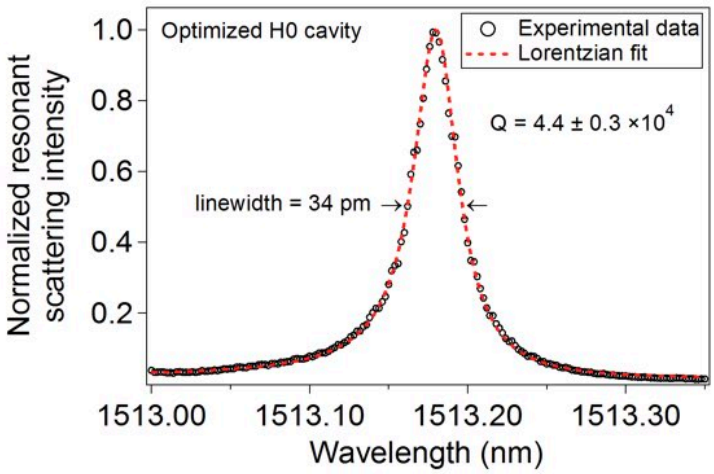
Opt. Lett. 37, 4588 (2012) & Appl. Phys. Lett. 102, 081120 (2013)

GaN and III-N

Record quality factor in GaN PhC

$Q_{meas.}$ = 44 000 (with injectors)

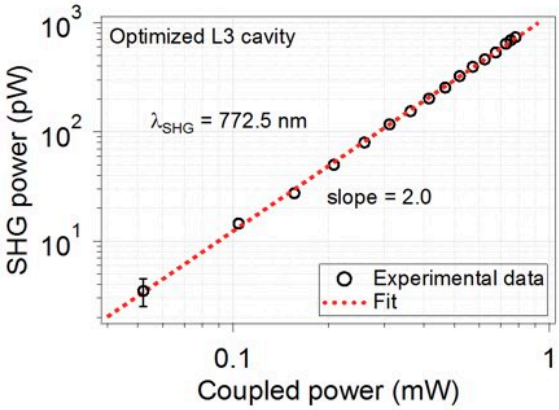
$Q_{theo.}$ = 80 000

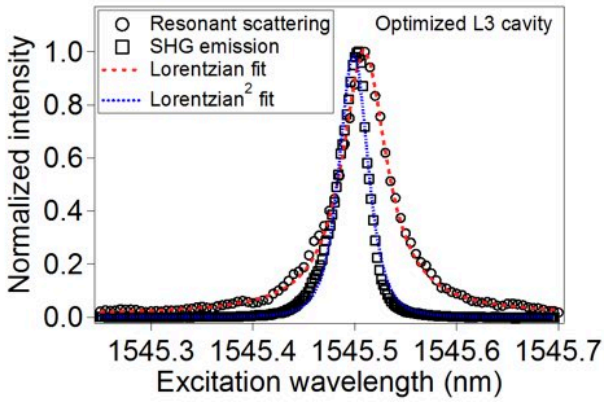


APL Phot. 2, 0331301 (2017)

GaN and III-N

Continuous-wave 2nd and 3rd harmonic generation





P_{SHG} = 0.74 nW for 0.78 mW input coupled in the cavity

$P_{SHG} / P^2_{coupled} = 2.4\times10^{-3}\ W^{-1}$

APL Phot. 2, 0331301 (2017)

That's all ...