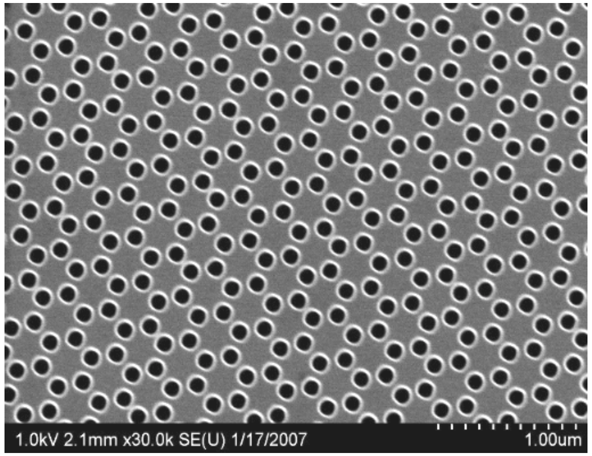
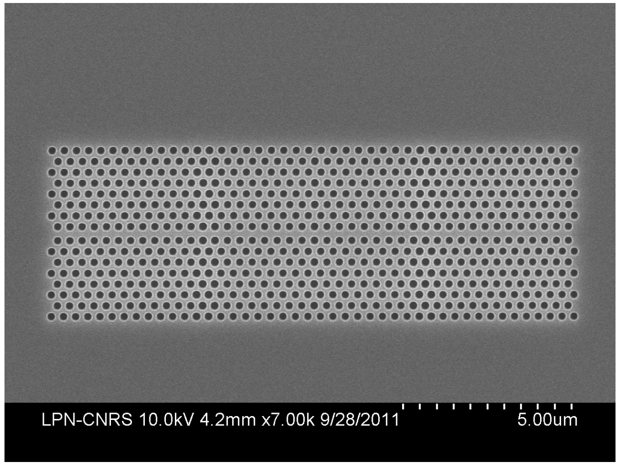
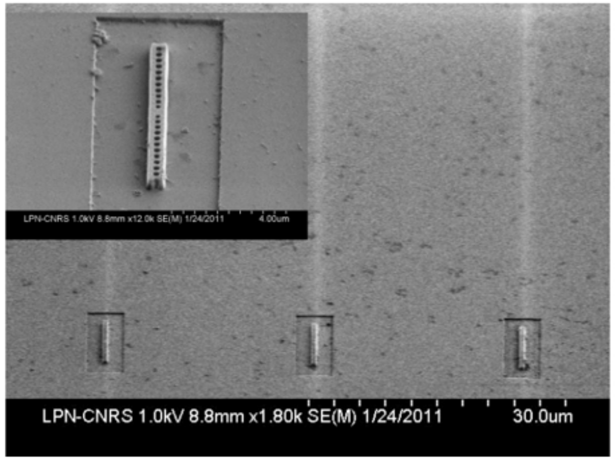
Nonlinear Photonic Crystals







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LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Laboratoire de Photonique et de Nanostructures

Staff:
42 researchers and academic staff
40 technical staff
40 PhD students and post-doctoral fellows

Research in the fields of nanosciences, nanofabrication, photonics & devices from materials and technologies to basic science and applications

Mainly III-V semiconductors

From Nanoscience...

...To Telecom/Photonics oriented basic research

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Motivations

Domain of physics called Nonlinear optics started right after the Laser invention as it enabled the availability of light sources sufficiently intense to observe these effects:

→ in 1961, experimental work by Franken et al on Second Harmonic generation
→ in 1962 theoretical work by Bloembergen et al on wave mixing

Note that Nonlinear optics phenomena were observed before (optical pumping, Pockels effect, Raman Scattering).

From that time onwards research on nonlinear optics lead to great discoveries: parametric sources (OPO, OPA), twin photon generation, soliton propagation in optical fibers, modulators….

→Integrated optics is today the frontier for nonlinear optics → efficient effects with mW incident power

→ **Photonic crystals as ideal materials for giant nonlinear processes**

Outline

I- BASICS ON NONLINEAR OPTICS

II- BASICS ON PHOTONIC CRYSTALS

III- NONLINEAR PHOTONIC CRYSTALS

IV- NANOLASERS

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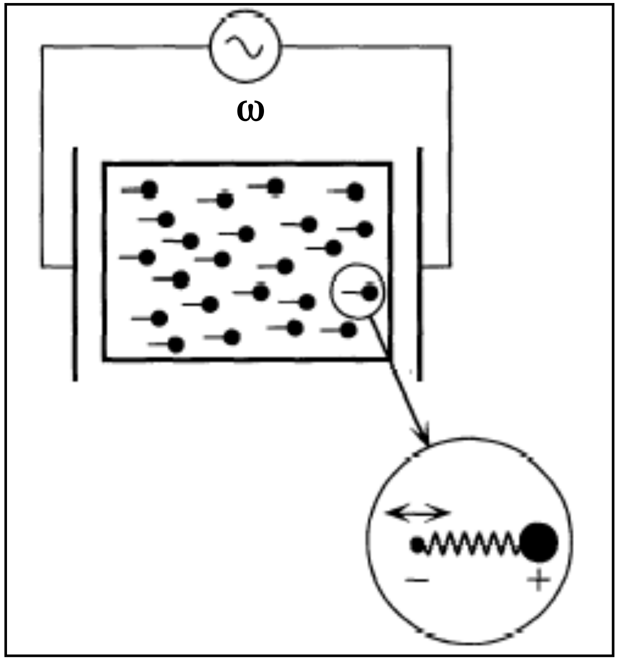
BASICS ON NONLINEAR OPTICS

1- General concept

2- Second order nonlinear process

3- Third order nonlinear process

BASICS ON NONLINEAR OPTICS: General Concept



Full Classical Approach: Lorentz Model
A dielectric material considered as an assembly of charged particle bound together.
In presence of an electric field, e- start to oscillate at ω frequency

→ **Polarisation** $\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E}$

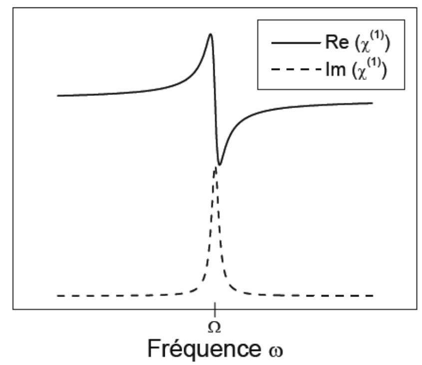
$\chi^{(1)}$ **linear susceptibility**

ω_0 **electron resonant frequency,** γ **damping factor, N electric dipoles density, m electron mass**

$$\varepsilon_r = \varepsilon' + i\varepsilon''$$

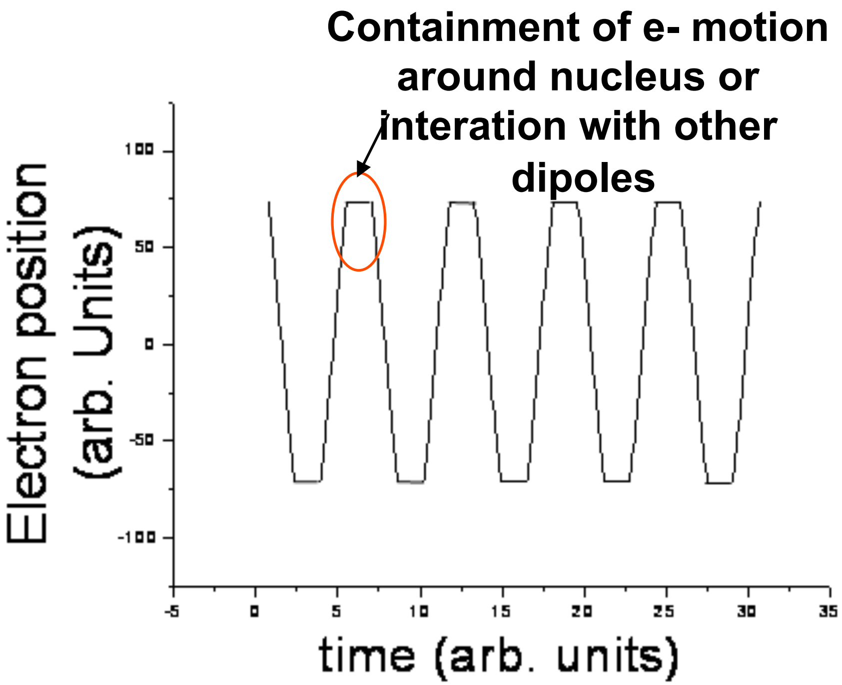
ε'=Re (1+$\chi^{(1)}$)

ε''=Im (1+$\chi^{(1)}$)



BASICS ON NONLINEAR OPTICS: General Concept

Now As the Electrical Field Field amplitude increases



→ Displacement of e- is nonlinear with field amplitude!

→ Polarisation which varies nonlinearly with the Electric Field!

BASICS ON NONLINEAR OPTICS: General Concept

→ Polarisation

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \chi^{(2)} \vec{E} : \vec{E} + \varepsilon_0 \chi^{(3)} \vec{E} : \vec{E} : \vec{E} + \ldots + \varepsilon_0 \chi^{(n)} \vec{E} : \vec{E} : \ldots : \vec{E} + \ldots$$

Linear polarisation

Nonlinear polarisation

Where $\chi^{(n)}$ (Tensor of order n+1) is the nonlinear susceptibility of order n

$\chi^{(n+1)} < \chi^{(n)}$ (Taylor development: perturbation theory)

$\chi^{(n)}$ related to the microscopic structure of the medium → quantum theory

BASICS ON NONLINEAR OPTICS: General Concept

Nonlinear polarisation = source term in wave propagation equation

$$\vec{\nabla} x \vec{\nabla} x \vec{E}(r,\omega) - \frac{\omega^2}{c^2}\varepsilon(\vec{r},\omega)\vec{E}(r,\omega) = \omega^2 \mu_0 \vec{P}_{NL}(\vec{r},\omega)$$

In general no analytical solution to the equation

→ Study of 2^{nd} and 3^{rd} order nonlinear effects

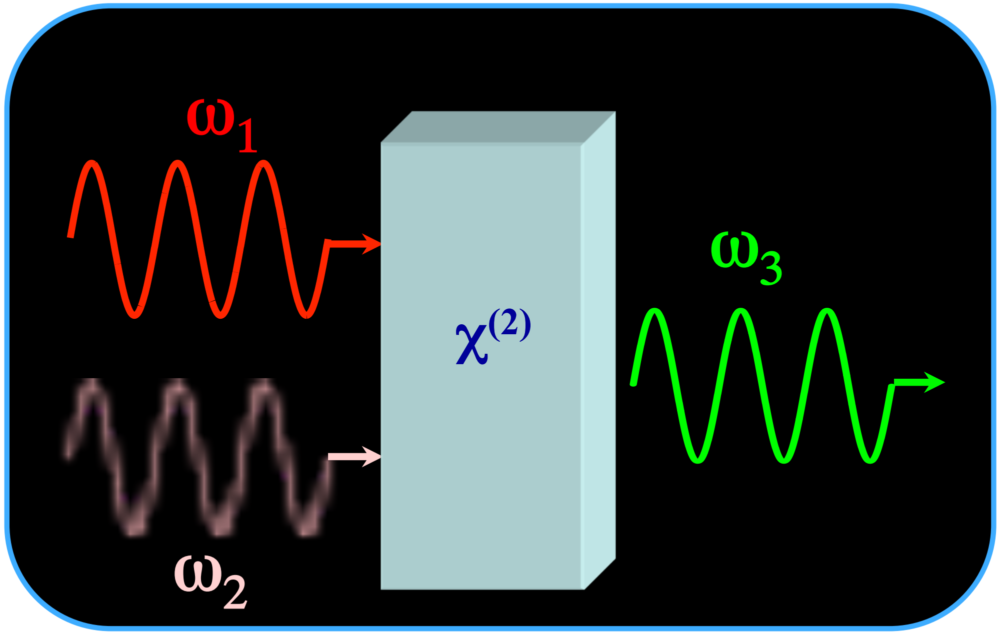
1- General concept

2- Second order nonlinear process

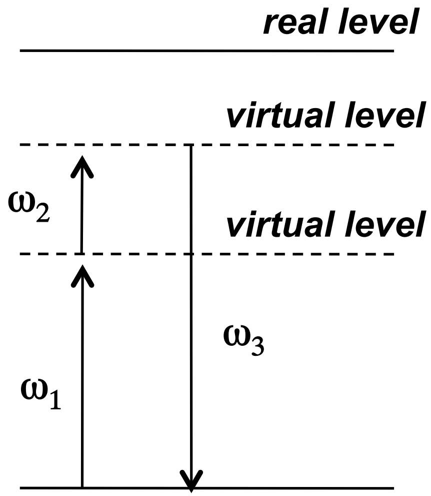
3- Third order nonlinear process

Second order nonlinear process

3-wave mixing



Quantum diagram



Only possible in non centro symmetric materials

$\omega_1+\omega_2=\omega_3$ **Sum frequency Generation**

or $\omega_1-\omega_2=\omega_3$ **Difference frequency Generation**

Set of coupled equations

$$\vec{\nabla}x\vec{\nabla}x\vec{E}(\vec{r},\omega_3)-\frac{\omega_3^2}{c^2}\varepsilon(\vec{r},\omega_3)\vec{E}(\vec{r},\omega_3)=\omega_3^2\mu_0\varepsilon_0\chi^{(2)}(-\omega_3;\omega_1,\omega_2):\vec{E}(\vec{r},\omega_1):\vec{E}(\vec{r},\omega_2)$$

$$\vec{\nabla}x\vec{\nabla}x\vec{E}(\vec{r},\omega_2)-\frac{\omega_2^2}{c^2}\varepsilon(\vec{r},\omega_2)\vec{E}(\vec{r},\omega_2)=\omega_2^2\mu_0\varepsilon_0\chi^{(2)}(-\omega_2;-\omega_1,\omega_3):\vec{E}^*(\vec{r},\omega_1):\vec{E}(\vec{r},\omega_3)$$

$$\vec{\nabla}x\vec{\nabla}x\vec{E}(\vec{r},\omega_1)-\frac{\omega_1^2}{c^2}\varepsilon(\vec{r},\omega_1)\vec{E}(\vec{r},\omega_1)=\omega_1^2\mu_0\varepsilon_0\chi^{(2)}(-\omega_1;-\omega_2,\omega_3):\vec{E}^*(\vec{r},\omega_2):\vec{E}(\vec{r},\omega_3)$$

To look at a simple case, let’s consider the material homogene, the interacting waves plane, their propagation colinear and parallel to z direction,

we can write: $$\vec{E}(\vec{r},\omega_i)=\left(\frac{1}{2}A_i(z)e^{jk_iz}+c.c.\right)\vec{u}_z$$

with $$k_i=\omega_i\frac{n(\omega_i)}{c}$$

→ scalar problem

Second order nonlinear process

coupled equations become

$$\frac{d^2A_3(z)}{dz^2} + 2jk_3 \frac{dA_3(z)}{dz} = -\omega_3^{\,2}\mu_0\chi^{(2)}(-\omega_3;\omega_1,\omega_2)A_1(z)A_2(z)e^{-j\Delta kz}$$

$$\frac{d^2A_2(z)}{dz^2} + 2jk_2 \frac{dA_2(z)}{dz} = -\omega_2^{\,2}\mu_0\chi^{(2)}(-\omega_2;-\omega_1,\omega_3)A_1^{\,*}(z)A_3(z)e^{j\Delta kz}$$

$$\frac{d^2A_1(z)}{dz^2} + 2jk_1 \frac{dA_1(z)}{dz} = -\omega_1^{\,2}\mu_0\chi^{(2)}(-\omega_1;-\omega_2,\omega_3)A_2^{\,*}(z)A_3(z)e^{j\Delta kz}$$

with $\Delta k = k_3 - k_2 - k_1$
phase mismatch between the wave propagating in the medium @ ω_3 and the generated wave @ ω_3

Slowly varying envelop approx: $\left|\frac{d^2A_i(z)}{dz^2}\right| << \left|2jk_i \frac{dA_i(z)}{dz}\right|$

$$\frac{dA_3(z)}{dz} = \frac{j\omega_3}{2cn(\omega_3)}\chi^{(2)}(-\omega_3;\omega_1,\omega_2)A_1(z)A_2(z)e^{j\Delta kz}$$

$$\frac{dA_2(z)}{dz} = \frac{j\omega_2}{2cn(\omega_2)}\chi^{(2)}(-\omega_2;-\omega_1,\omega_3)A_1^{\,*}(z)A_3(z)e^{-j\Delta kz}$$

$$\frac{dA_1(z)}{dz} = \frac{j\omega_1}{2cn(\omega_1)}\chi^{(2)}(-\omega_1;-\omega_2,\omega_3)A_2^{\,*}(z)A_3(z)e^{j\Delta kz}$$

Second harmonic generation

$\omega_1 = \omega_2 = \omega$

$\omega_3 = 2\omega$

$$\frac{dA_{2\omega}(z)}{dz} = \frac{j\omega}{cn_{2\omega}} \chi^{(2)}(-2\omega;\omega,\omega) A_\omega^{\;2}(z) e^{-j\Delta kz}$$

$$\frac{dA_{\omega}(z)}{dz} = \frac{j\omega}{2cn_{\omega}} \chi^{(2)}(-\omega;-\omega,2\omega) A_\omega^{\;*}(z) A_{2\omega}(z) e^{j\Delta kz}$$

weak conversion effiency → non depletion of the fundamental field → A_ω=cte

CONVERSION EFFICIENCY:

$$\eta(z) = \frac{I_{2\omega}(z)}{I_\omega} = \frac{2\pi^2}{\varepsilon_0 c\lambda^2} \frac{\chi^{(2)\,2}}{n_\omega^2 n_{2\omega}} I_\omega(0) \left[\frac{\sin\left(\Delta k\, z/2 \right)}{\Delta k/2} \right]^2$$

varies linearly with intensity of the fundamental frequency

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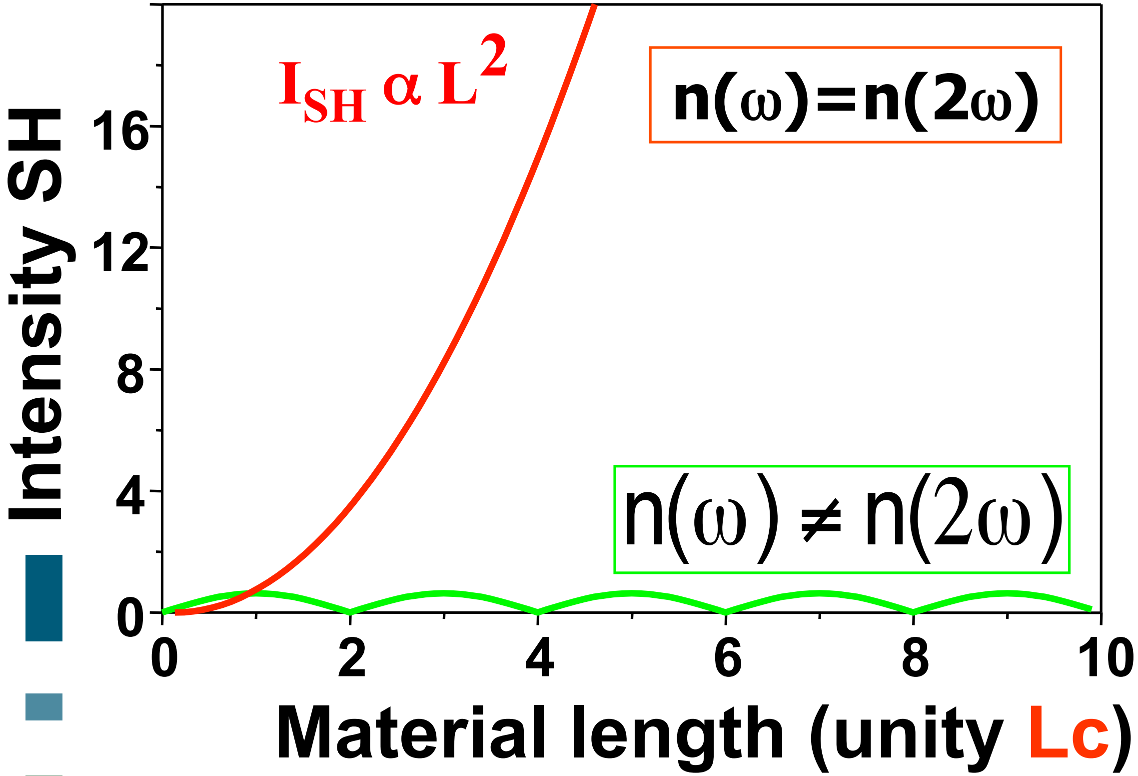
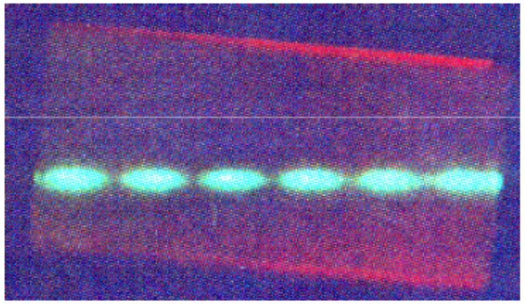
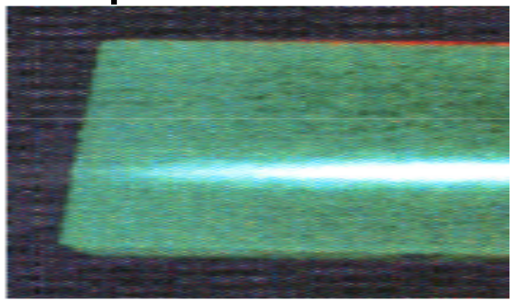
Second order nonlinear process



Non phase matched



phase matched



coherence length

$$L_c = \frac{\lambda}{4|n_{2\omega} - n_{\omega}|}$$

→Phasematching is primordial for high conversion efficiencies!

→ Photonic crystals for dispersion engineering!

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OTHER TYPES OF SECOND ORDER PHENOMENA:

Parametric generation/amplification: $\omega_3 \rightarrow \omega_1 + \omega_2$ **widely tunable sources (OPO,OPAs), optical gating techniques**

Twin photon generation : $2\omega \rightarrow \omega + \omega$ **generation of undistinguishable photons for quantum optics**

Pockels effect: 0 (DC voltage)$\rightarrow \omega - \omega$ **- Control of polarisation direction (Pockels cells), control of phase shift for optical modulation (nonlinear Mach-Zender)**

BASICS ON NONLINEAR OPTICS

1- General concept

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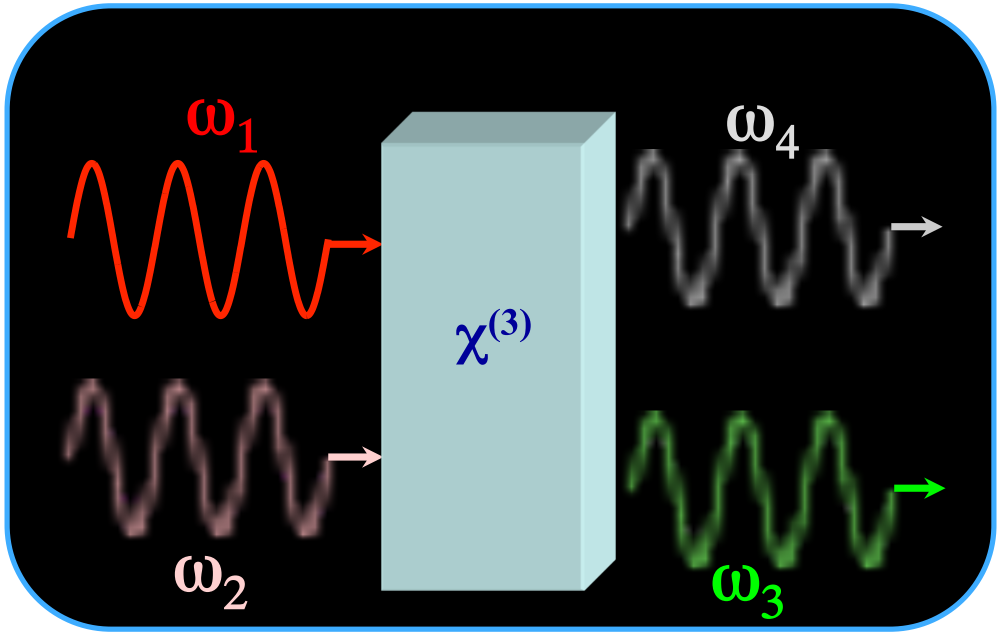
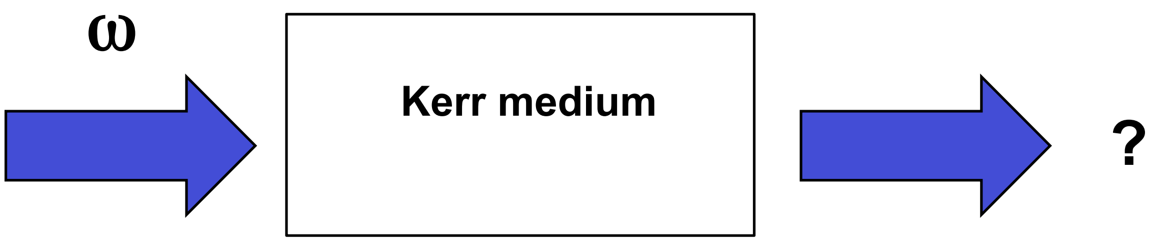
$\chi^{(3)}$ **Processes:**



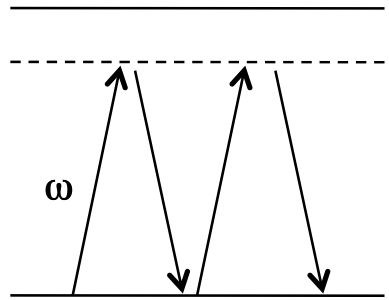
- 3^4 possible processes!
- Most common: Kerr effect, FWM, stimulated scattering, THG

Third order nonlinear process

Kerr effect: $\omega - \omega + \omega \rightarrow \omega$



Quantum diagram



Nonlinear Polarisation: $$P^{(3)}(z,\omega) = \frac{3\varepsilon_0}{8}\chi^{(3)}(-\omega;\omega,-\omega,\omega)A_\omega(z)A_\omega^{*}(z)A_\omega(z)e^{jk_\omega z} + c.c.$$

which gives for the wave equation: $$\frac{d^2E(z,\omega)}{dz^2} + \frac{\omega^2}{c^2}\left(n_\omega + \frac{3\chi^{(3)}(-\omega;\omega,-\omega,\omega)}{4n_\omega^2 c\varepsilon_0}I_\omega(z,\omega)\right)E(z,\omega) = 0$$

→ **control on refractive index via optical intensity!**

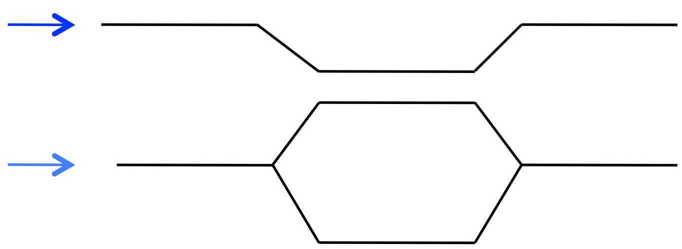
→ **opens the way to control light by light!**

Third order nonlinear process

Application of Kerr effect:

- Solitons: self phase modulation which compensates chromatic dispersion or self focusing which compensates diffraction

- Optical modulation in nonlinear interferometer or resonator



- Optical bistability in nonlinear resonator

Origin of nonlinearity

A lot of physical effect lead to the dependence of the refractive index with the field intensity. One can distinguish:

- Intrinsic nonlinearity

Light interacts with the electron cloud: no “real” energy exchange between light and matter
→transparent materials
→instantaneous
→ nonlinear refractive index n_2=2.7 .10^{-16} cm^2/W (for silica – x100 for Si)

- Dynamic nonlinearity

Light exchange energy with the matter. For example, thermal effects, absorption and refractive index change linked to change in carrier density
→energy dissipation
→ not instantaneous, depend on the dynamics of relaxation of the considered effect:
Thermal effects: heat dissipation occurs in microsecond
Electronic effect: linked to carrier life (ns)
→ nonlinear refractive index $n_2=10^{-6}$ cm^2/W (thermal effects)
$n_2=10^{-6}$ cm^2/W (carrier density change)

BASICS ON NONLINEAR OPTICS: SUMMARY

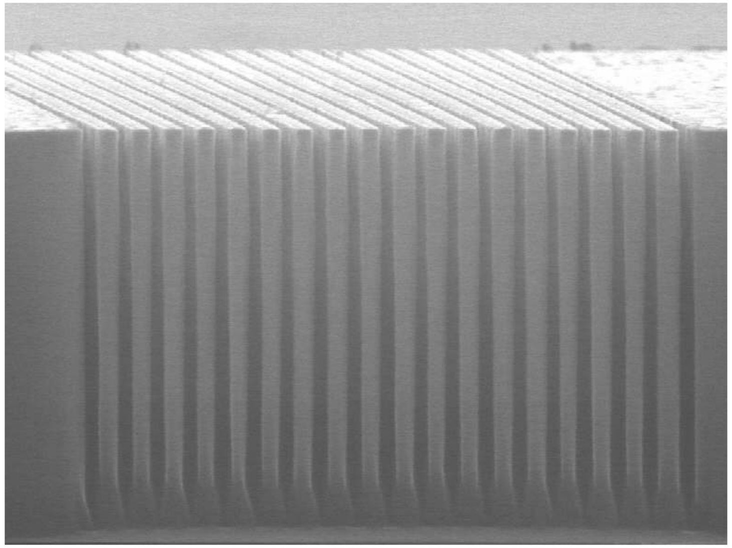
How to get large effects:

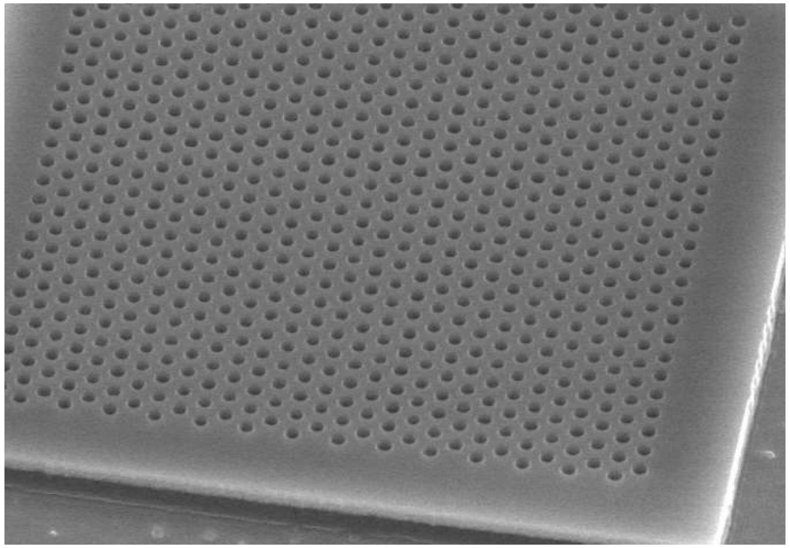
$$\vec{P} = \varepsilon_0 \chi^{(2)} \vec{E} : \vec{E} + \varepsilon_0 \chi^{(3)} \vec{E} : \vec{E} : \vec{E} + \ldots + \varepsilon_0 \chi^{(n)} \vec{E} : \vec{E} : \ldots : \vec{E} + \ldots$$

- $\chi^{(i)}$ large (material property)
- E high (confinement, cavity)
- phase-matching and adaptation of group velocity (wave mixing)

Now the question is what system is most appropriate?

The answer lies …….
……….in being à la mode





photonic crystals

BASICS ON PHOTONIC CRYSTALS

1- Photonic Crystals: “What’s in a name?”

2- Fabrication

3- Summary on their usefulness

BASICS ON PHOTONIC CRYSTALS

1- Photonic Crystals: “What’s in a name?”

Eli Yablonovitch, Optics and Photonics News March 2007

2- Fabrication

3- Summary on their usefulness

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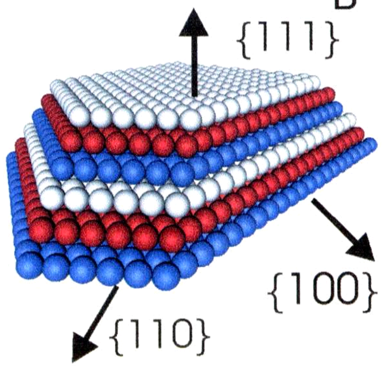
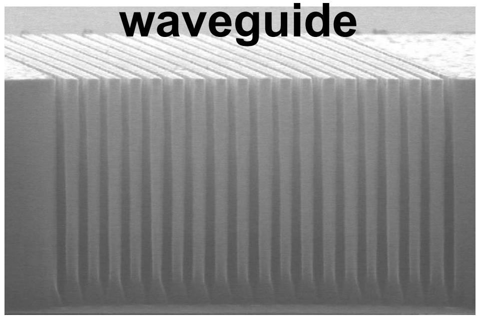
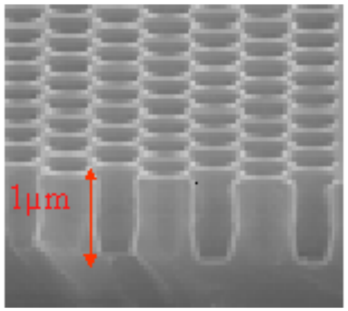
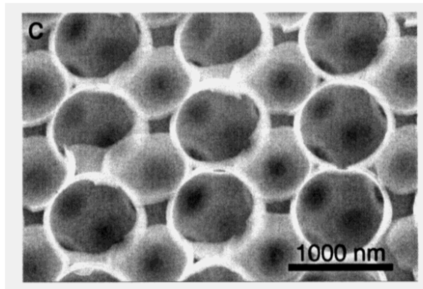
BASICS ON PHOTONIC CRYSTALS: General Concept

Materials with wavelength scale periodic modulation of refractive index

(E. Yablonovitch, *Phys. Rev. Lett.* 58 (1987) and S. John, *Phys. Rev. Lett.* 58 (1987))

1D	2D	3D
multilayer film	square lattice of dielectric columns surrounded by air	spheres in a FCC configuration 
AlGaAs/air waveguide 	AlGaAs/air 	inverted opals 

BASICS ON PHOTONIC CRYSTALS: General Concept

How do PhCs control the flow of light?

Semiconductor crystal → Periodic potential → Energy Gaps

Photonic crystal → Periodic dielectric function (refractive index) → Photonic Band Gaps

Maxwell's equations + dielectric constant periodicity → Dispersion relation: $\mathbf{K} = \mathbf{K}(\omega, \theta)$

K real ⟺ propagating modes

K complex ⟺ evanescent modes: Photonic Band Gaps

See Sakoda, Joanopoulos books…

BASICS ON PHOTONIC CRYSTALS: General Concept

Propagation equations:

$$\frac{1}{\varepsilon(\vec{r})}\vec{\nabla}x\left\{\vec{\nabla}x\vec{E}(\vec{r})\right\} = \frac{\omega^2}{c^2}\vec{E}(\vec{r})$$

$$\vec{\nabla}x\left\{\frac{1}{\varepsilon(\vec{r})}\vec{\nabla}x\vec{H}(\vec{r})\right\} = \frac{\omega^2}{c^2}\vec{H}(\vec{r})$$

In general, the solutions are not analytical

→Numerical tools have been developed for solving the equations and obtaining the dispersion relation. One can site:

- Plane wave expansion (MIT MPB) or Guided mode expansion (Pavia)

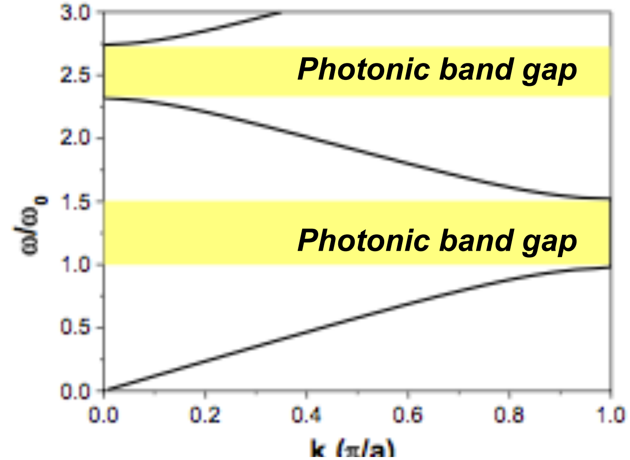
- Finite difference time domain method

- Scattering Matrix Method

BASICS ON PHOTONIC CRYSTALS: General Concept

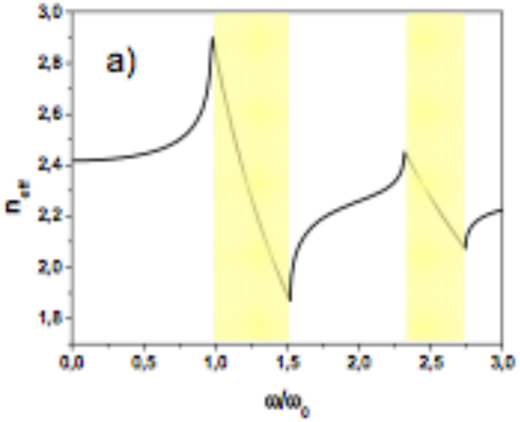
In 1D the problem is ANALYTICAL and the main properties can be derived

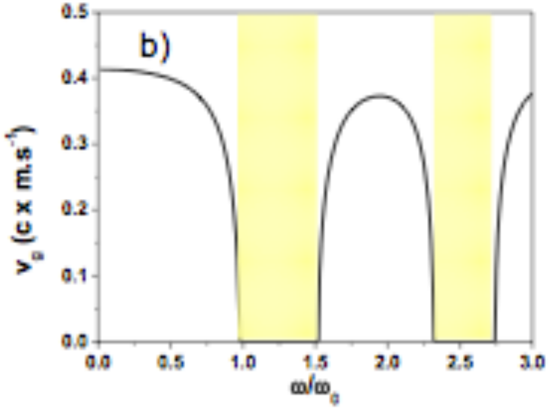
Bragg Mirror



→Band Gap wavelength depends on the optical thicknesses of the layers (Max when λ/4n : λ/4n)

→ Width of the band gap increases with index contrast



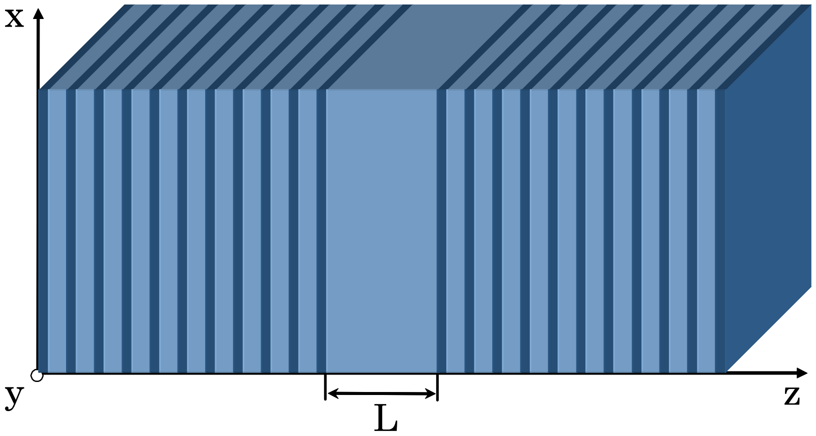


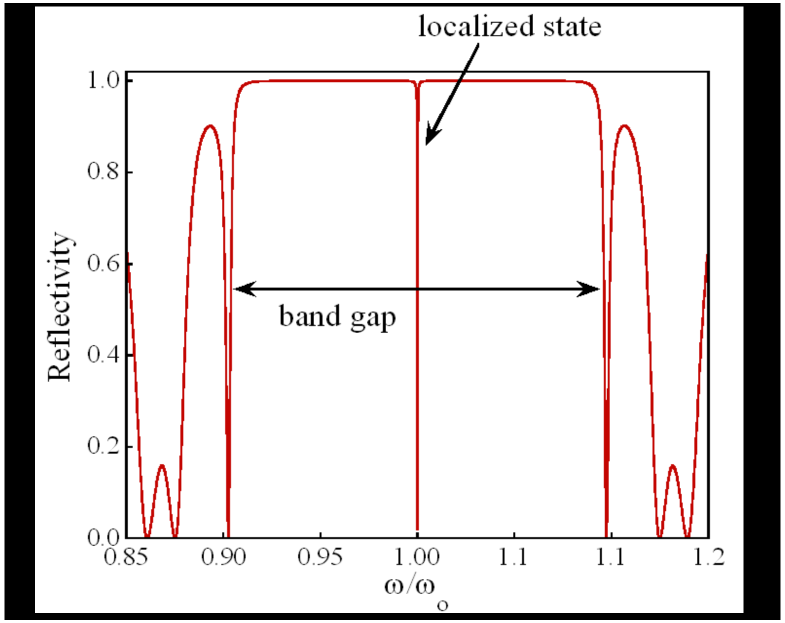
→ anomalous dispersion in the band gap
→ v_g goes to 0 at the band edges

BASICS ON PHOTONIC CRYSTALS: General Concept

1D microcavity

Defect in the periodicity → State in the band gap



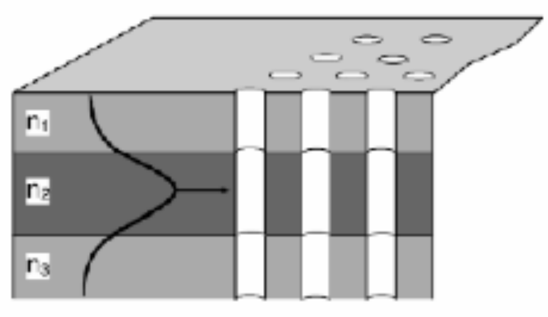


$Q=\omega_0\tau_p/2\approx\lambda/\Delta\lambda$

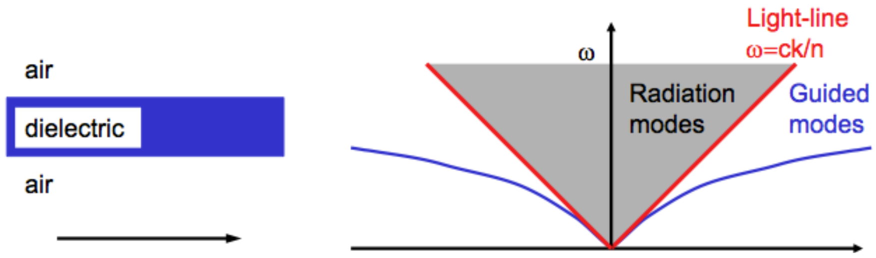
Quality factor = number of cavity roundtrips

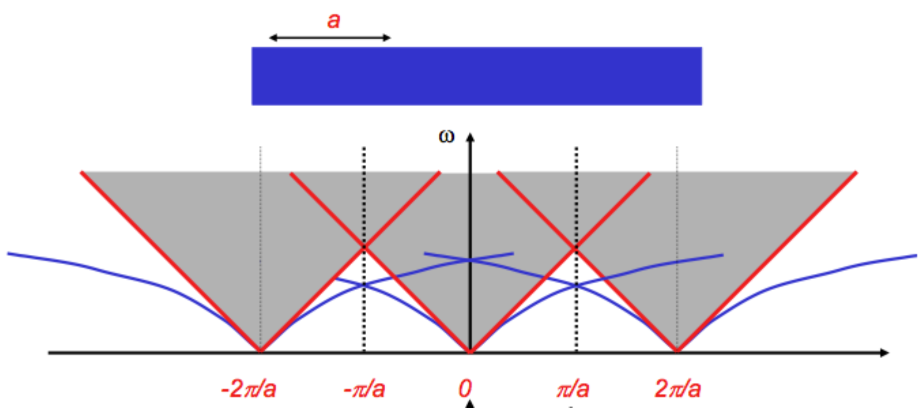
BASICS ON PHOTONIC CRYSTALS: General Concept

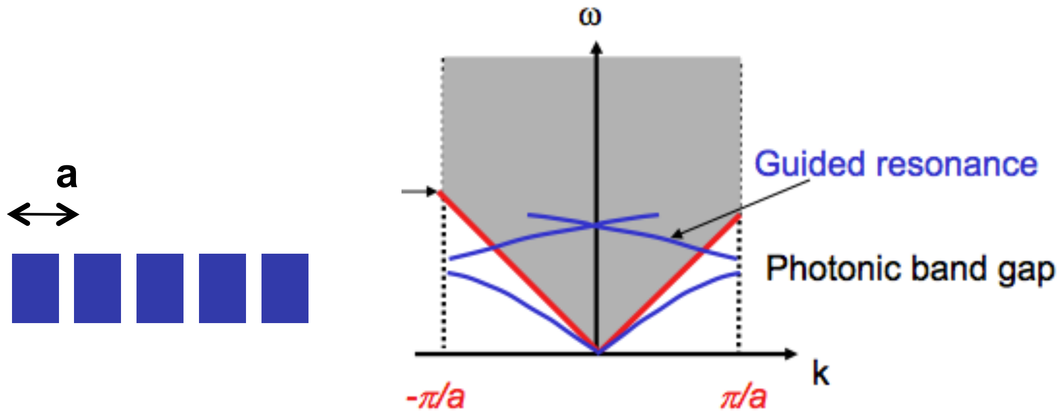
2D photonic crystals slabs



→ In plane light propagation is determined by the 2D structuration
→ In the third direction light is confined by total internal reflection



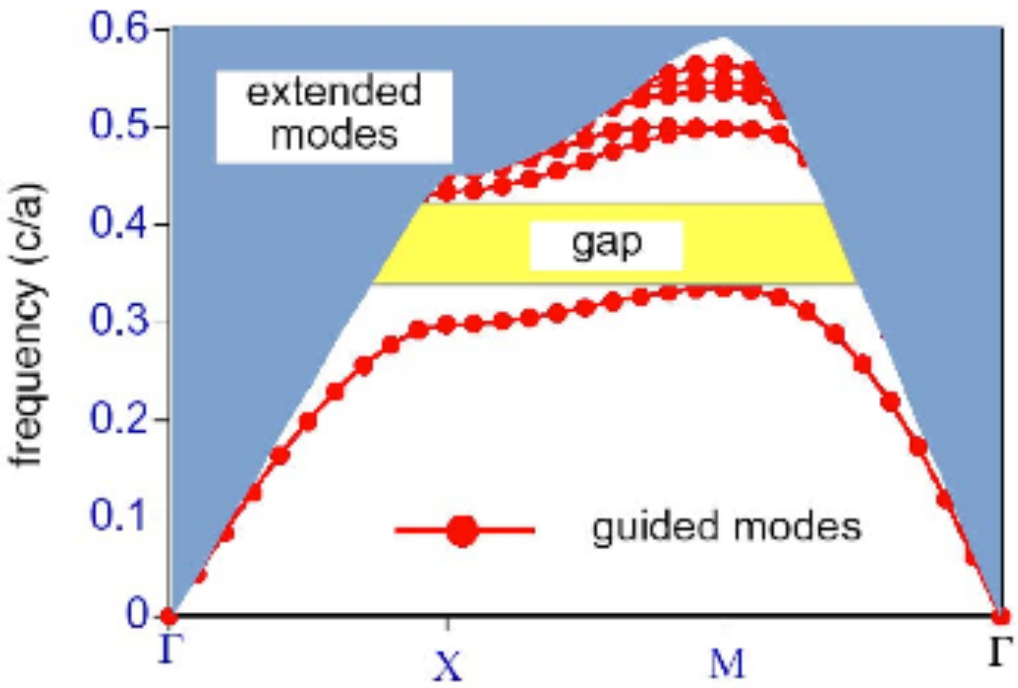




→ some modes are leaky!

BASICS ON PHOTONIC CRYSTALS: General Concept

Band structure for triangular lattice of holes in a slab
TE polarisation

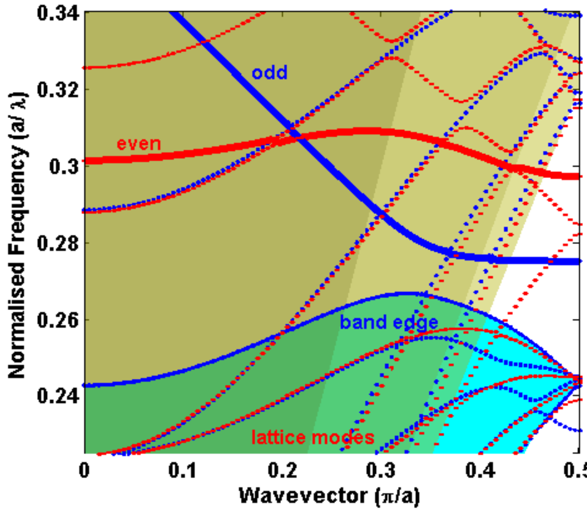


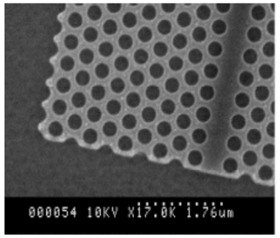
Almost the same properties than in 1D but:
- Increase control of light propagation (2D)
- coupling of guided modes to the radiative modes → air bridge membrane to limit the losses

BASICS ON PHOTONIC CRYSTALS: General Concept

Defects in 2D photonic crystals

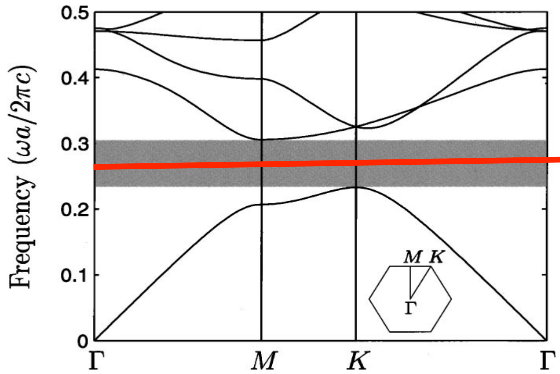
Line defect waveguides

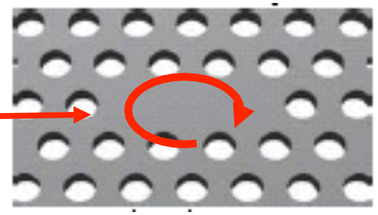




- Regular step index waveguide for some frequencies
- Light guided thanks to the band gap → Slow light!

Localised defect → nanocavities





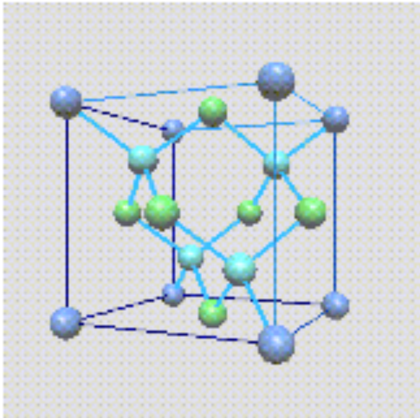
- Various Design for obtaining high Q (10^9)
→smart confinement by Fourier space analysis
- Diffraction limited volume $(\lambda/2n)^3$

Ultimate cavities?

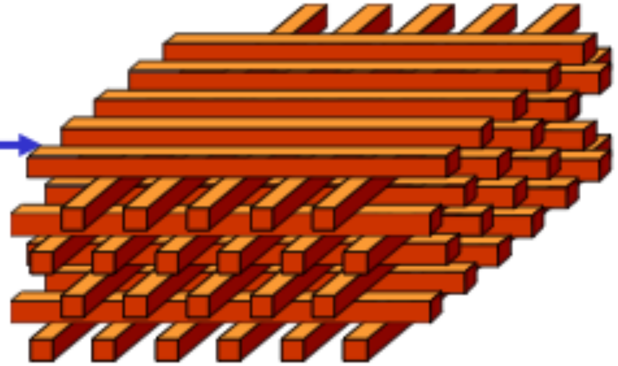
BASICS ON PHOTONIC CRYSTALS: General Concept

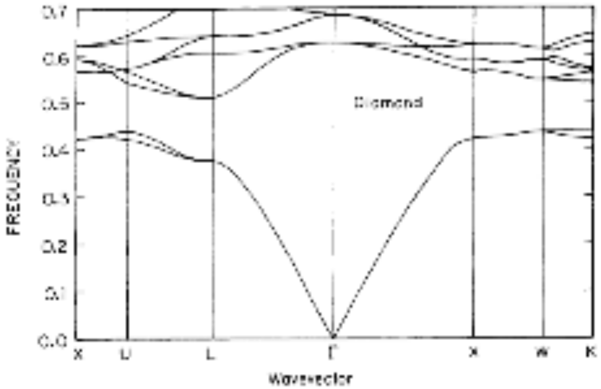
3D photonic crystals

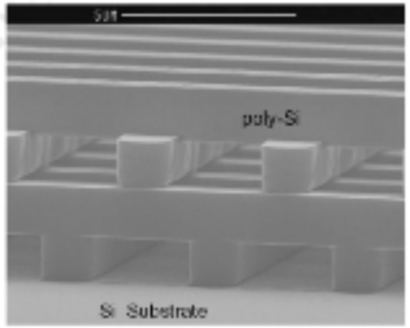
Diamond structure



Practical PhC







Full photonic band gap

1- Photonic Crystals: “What’s in a name?”

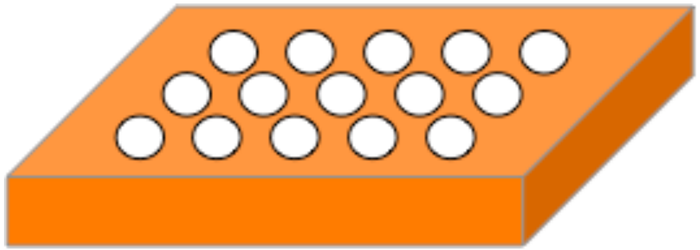
2- Fabrication

3- Summary on their usefulness

BASICS ON PHOTONIC CRYSTALS: Fabrication

Semiconductor 2D photonic crystals using planar technology

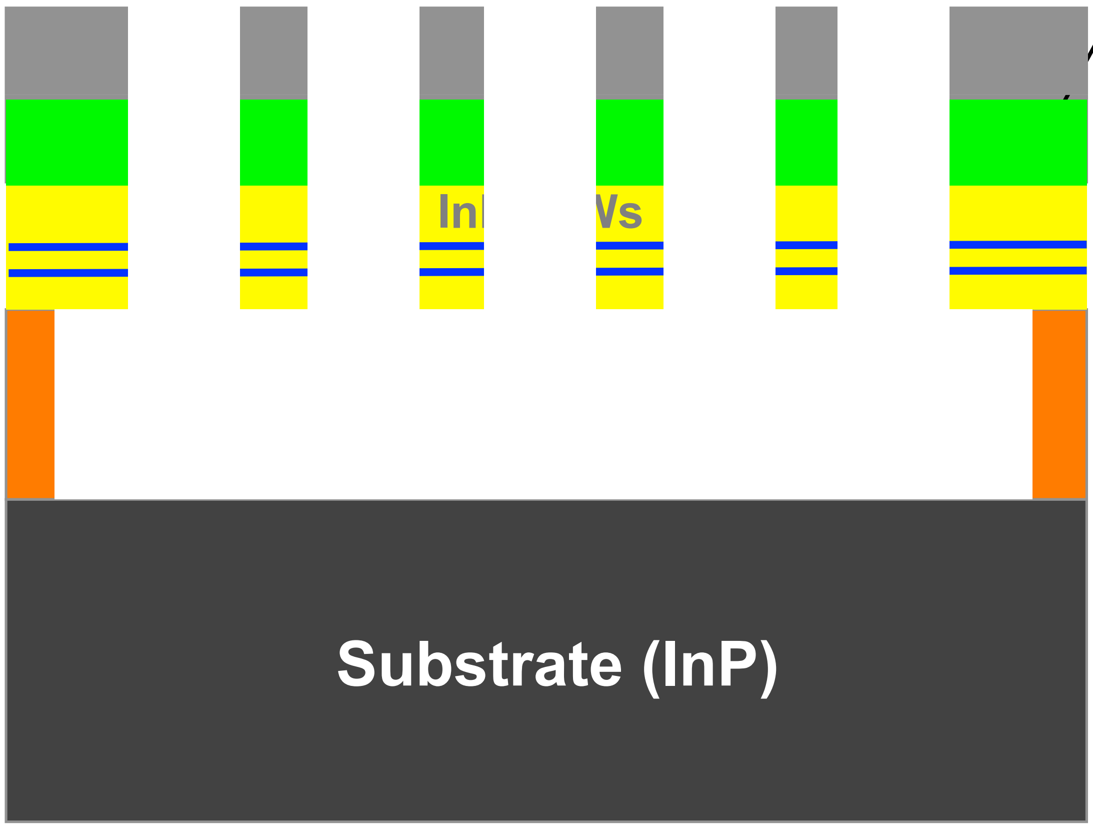
Goal: Obtaining a 2D PhC operating at telecom wavelength (1.55 microns). Lattice of holes drilled in a membrane suspended in air

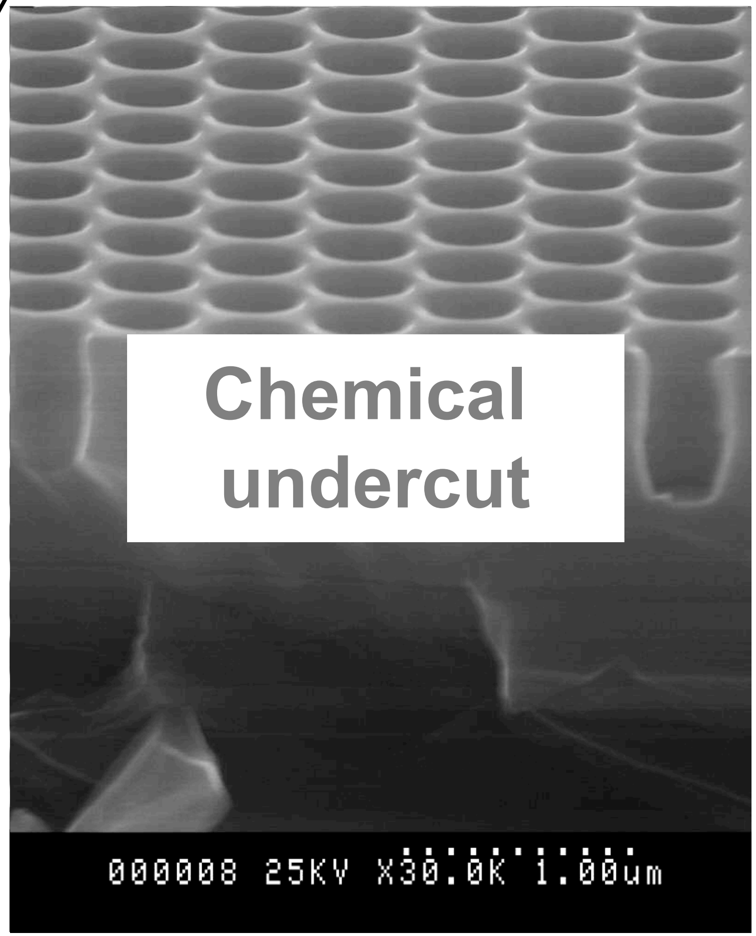


lattice constant= 400nm
holes diameter=200nm
membrane thickness=250nm

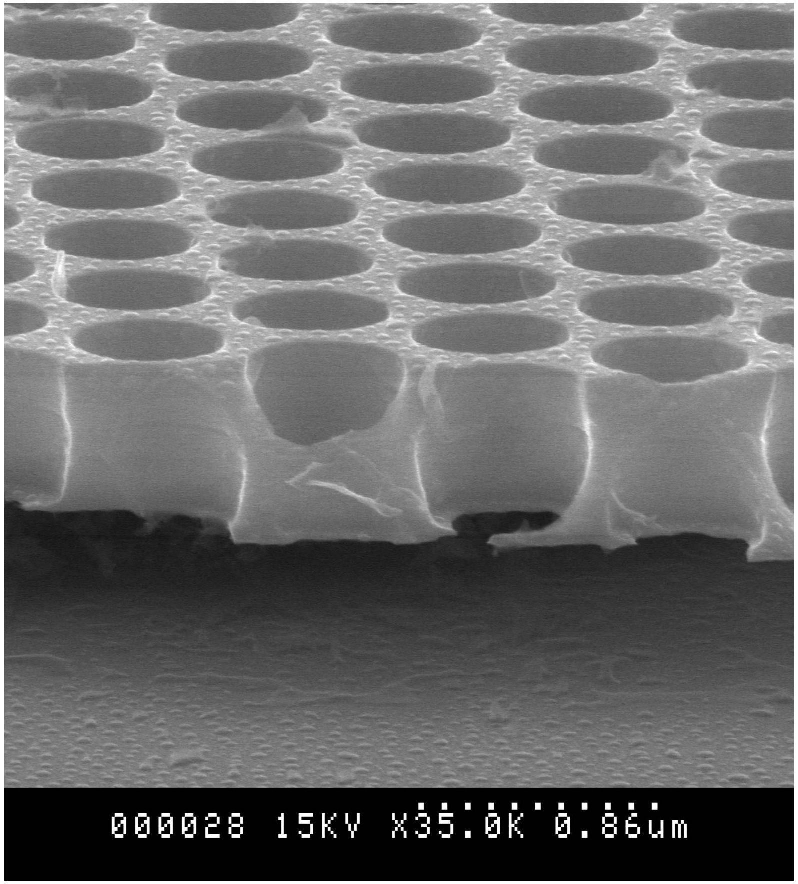
ebeam Lithography

electro-sensitive resist (PMMA)





Suspended membrane



BASICS ON PHOTONIC CRYSTALS

1- Photonic Crystals: “What’s in a name?”

2- Fabrication

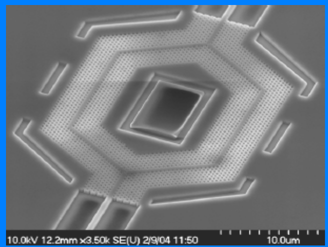
3- Summary on their usefulness

Summary on their usefulness: Some exciting studies on PhC

On propagation

→ **Compact waveguides**

R. De la Rue et al, New J. Phys. 8 (2006)



→ **Negative refraction**

A. Berrier et al, Phys. Rev. Lett. 93, 073902 (2004) (KTH,LPN)

→ **Non-diffractive propagation…**

D.W. Prather, Opt. Letters 29, 50 (2004)

On light/matter interaction

→ **Control of spontaneous emission (QED experiment)**

Vuckovic @stanford

→ **nanolasers (LPN, KAIST,…)**

→ **beam steering (Noda)**

→ **Nonlinear Optics (Harmonic generation, all optical data processing…)**

THALES, NTT, IBM, KAIST, MIT, St Andrews, Roma, Toronto, …

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LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

BASICS ON NONLINEAR OPTICS: SUMMARY

How to get large effects:

$$\vec{P} = \varepsilon_0 \chi^{(2)} \vec{E}:\vec{E} + \varepsilon_0 \chi^{(3)} \vec{E}:\vec{E}:\vec{E} + \ldots + \varepsilon_0 \chi^{(n)} \vec{E}:\vec{E}:\ldots:\vec{E} + \ldots$$

- **$\chi^{(i)}$ large (material property)**
- **E high (confinement, cavity)**
- **phase-matching and adaptation of group velocity (wave mixing)**

Why nonlinear optics and Photonic crystals?

- Photonic crystals for nonlinear optics

PhC enables a quasi perfect control on light propagation:

- high Q cavities, Slow light waveguides → High intensities in materials
- Dispersion engineering for phase matching

- Nonlinear optics for photonic crystals

nonlinear optics opens the functionality portfolio of PhC:

- Sources
- manipulation of light by light

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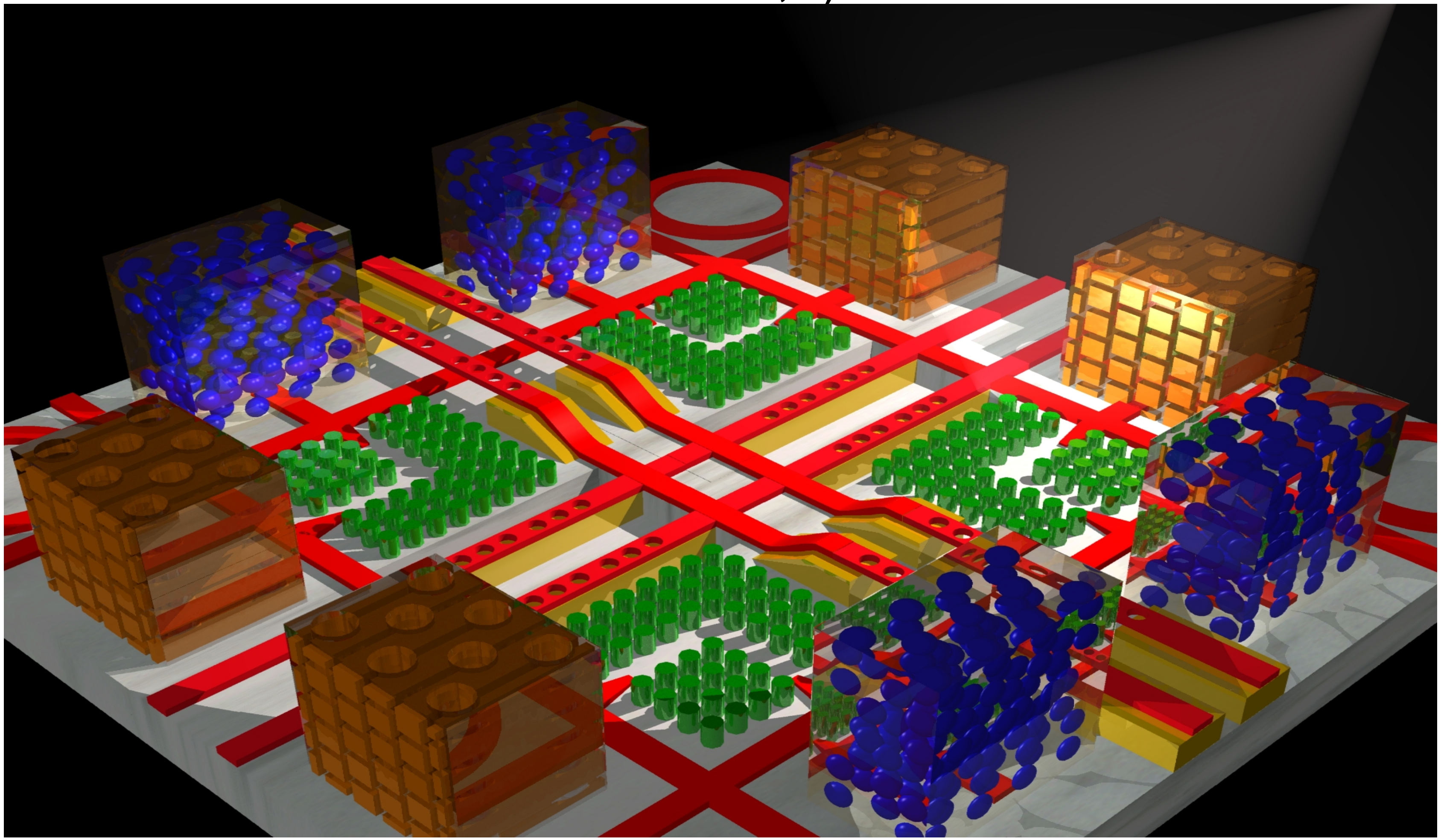
Photonic Metropolis by MIT

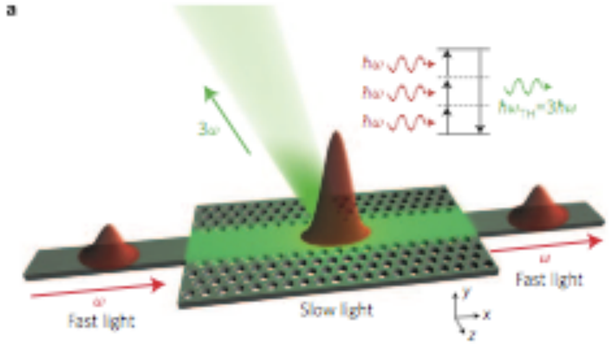
Passive functionalities (filtering, waveguiding….) + Active functionalities (sources, switches, memories,…)

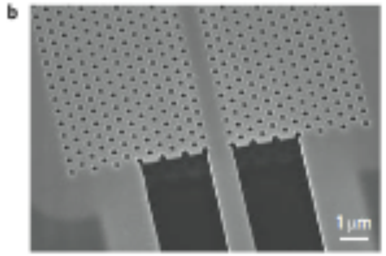


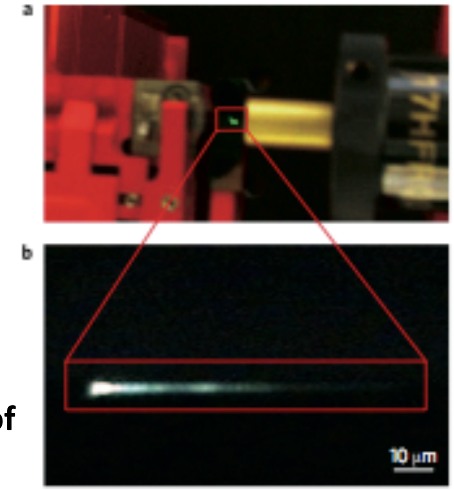
http://ab-initio.mit.edu/photons/micropolis.html

Some work all over the world

Green light emission in silicon through slow-light enhanced third-harmonic generation in photonic-crystal waveguides

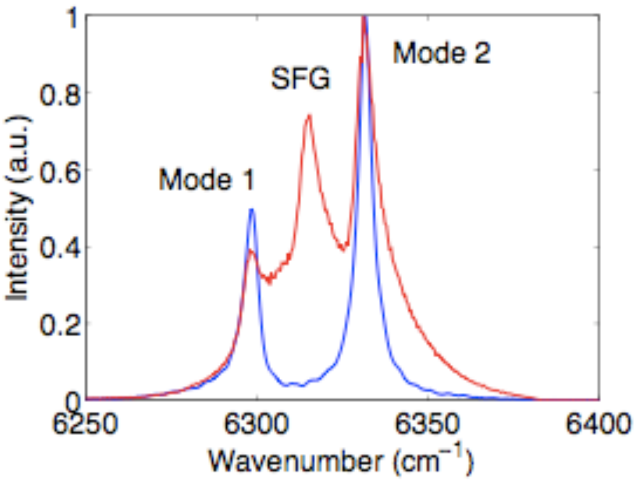




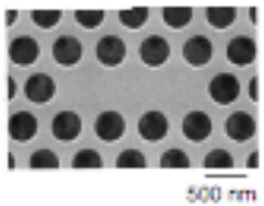


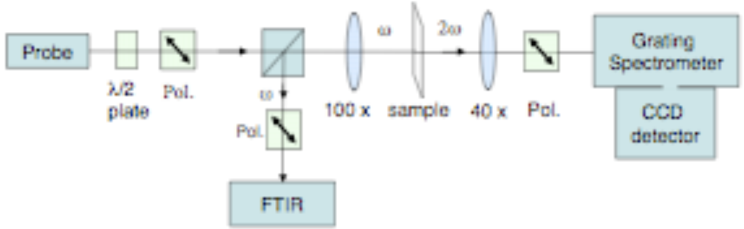
CUDOS, Institute for Photonic Optical Sciences (IPOS), Australia and University of St Andrews, UK. (2009)

Second-order nonlinear mixing in planar photonic crystal microcavities



Harvard university, USA and University of British Columbia, Canada (2006)

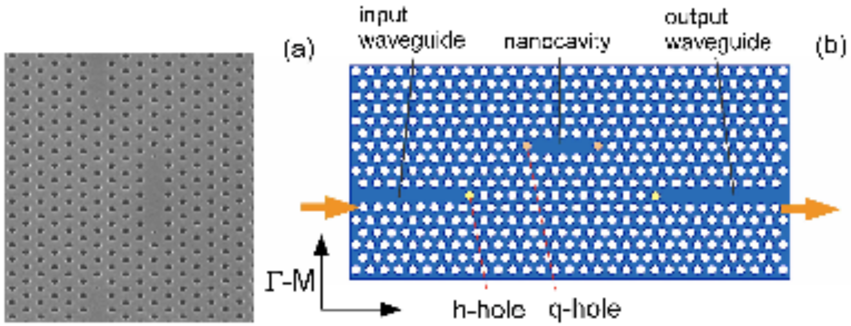


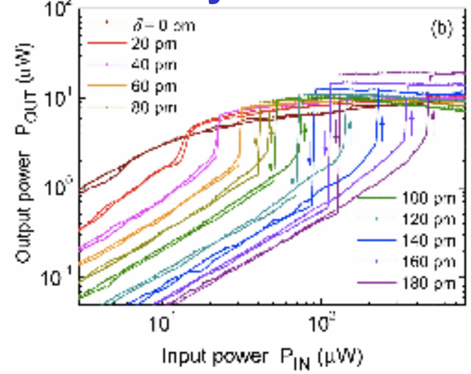


Efficiency=10^-13

Some work all over the world

All-optical bistable switching in ultra-small high-Q Si photonic-crystal nanocavities. Due to high Q/V ratio, the switching energy is extremely low.

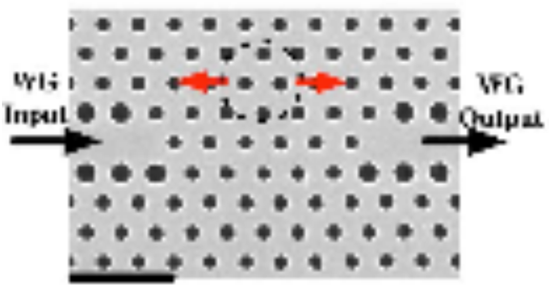


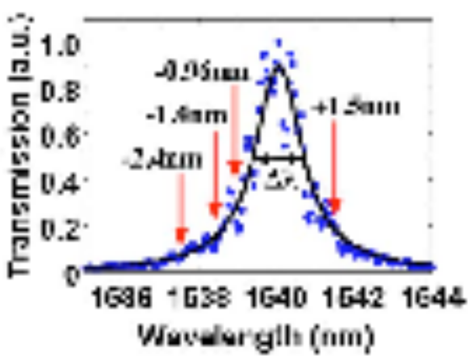


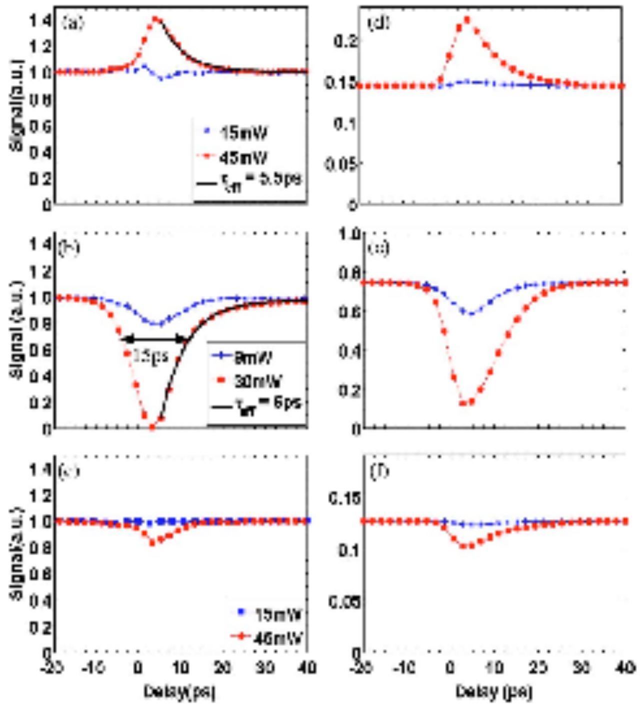
NTT basic research laboratory, Japan (2005)

Ultrafast all-optical modulation in GaAs photonic crystal cavities

Thales, LPN, Columbia Univ. (2010)

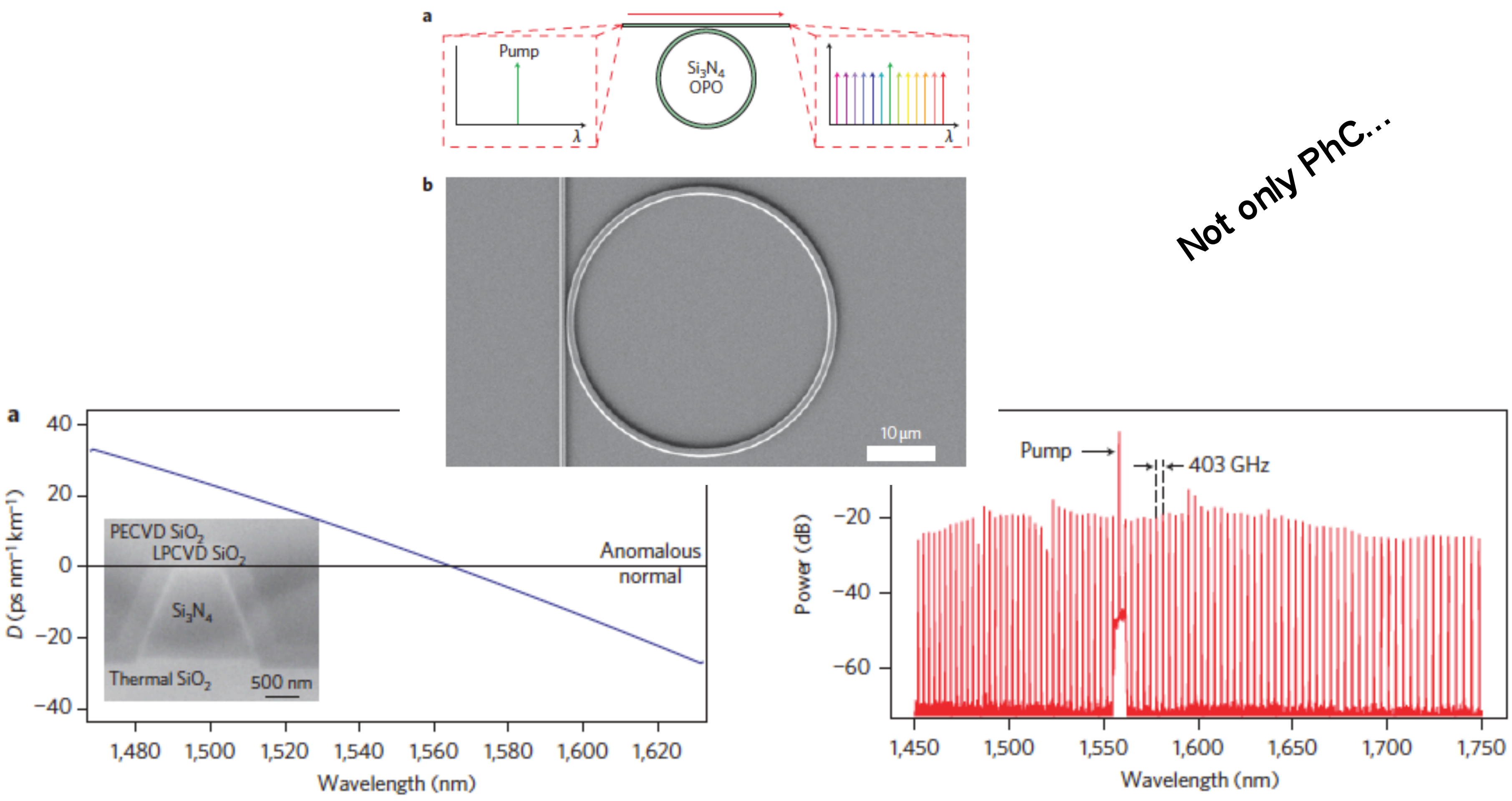






Some work all over the world

Frequency comb generation based on FWM in SiN-based ring resonator



Not only PhC…

Cornell Univ, USA (2010)

NONLINEAR SEMICONDUCTOR PHOTONIC CRYSTALS

1- Ultracompact wavelength converter ($\chi^{(2)}$)

2- All-optical ultrafast switching

3- Solitons propagation

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NONLINEAR PHOTONIC CRYSTALS

1- Ultracompact wavelength converter ($\chi^{(2)}$)

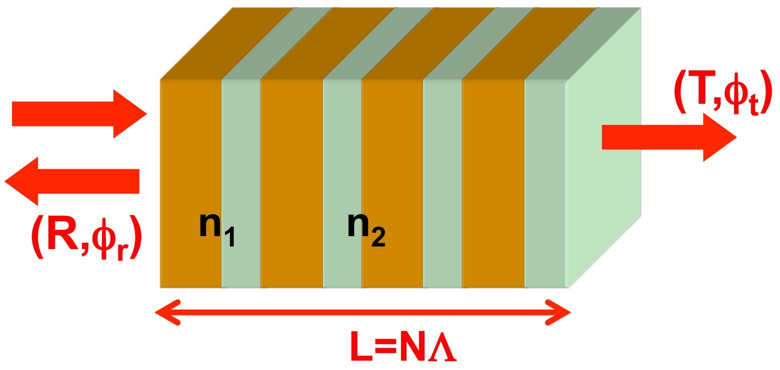
→ ***Second harmonic generation in 1D PhC***

→ ***Second harmonic generation in 2D PhC***

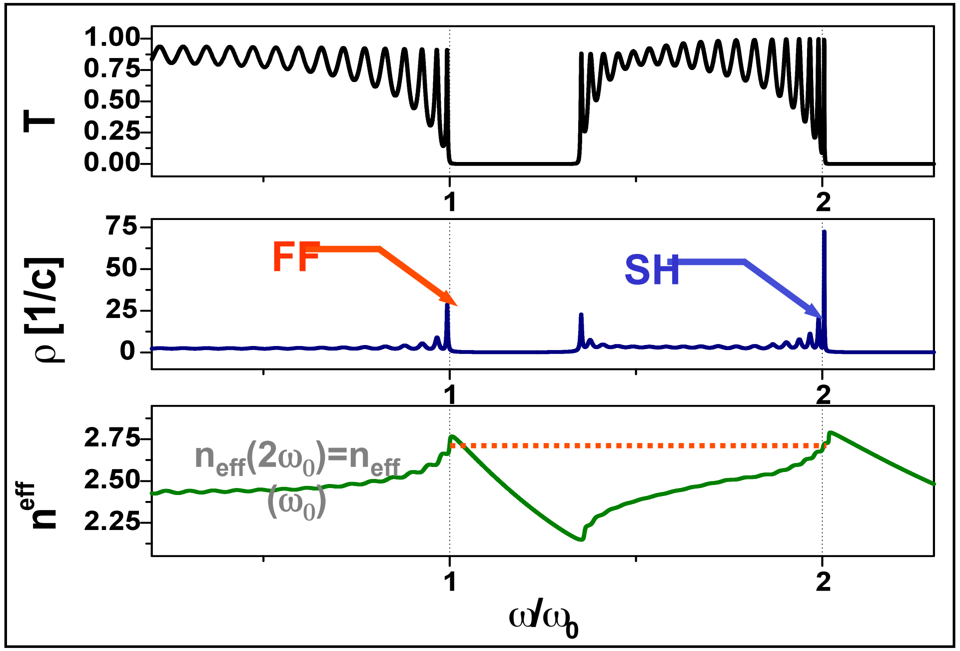
2- All-optical ultrafast switching

3- Solitons propagation

Second harmonic generation in AlGaAs/AlOx Bragg mirrors



M. Centini *et al.*, Phys. Rev. E 60, 4891 (1999). (Theory)
G. D'Aguanno *et al.*, Phys. Rev. E 64, 016609 (2001). (Theory)



→ Use anomalous dispersion at the band-edges to obtain phase matching to compensate chromatic dispersion
@1.55µm $\Delta n=0.24$ → $L_c=1.6\mu m$! in $Al_{.3}Ga_{.7}As$

Ultracompact device!

→Use increased mode density ($1/v_g$) to go from

~~$\eta \propto L^2$~~ → $\eta \propto L^6$

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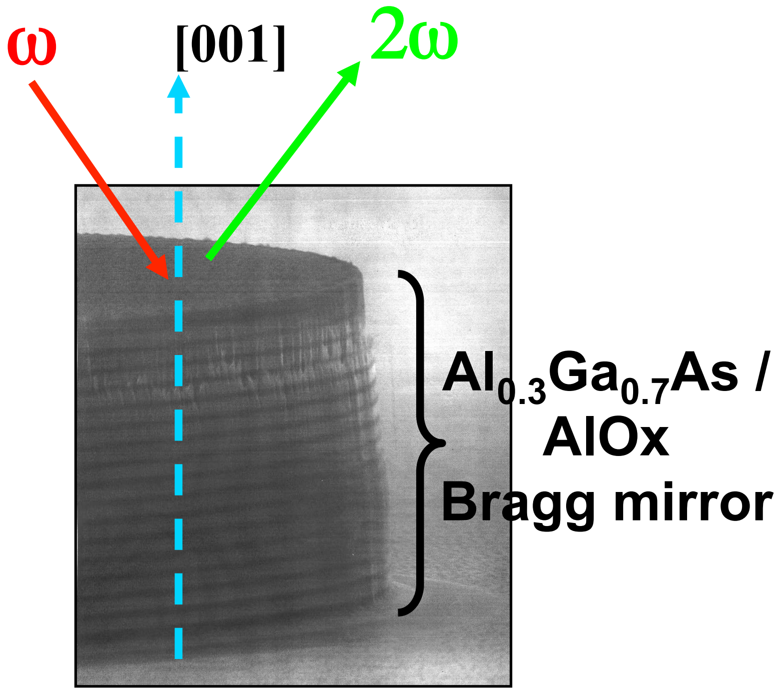
Second harmonic generation in Bragg mirrors

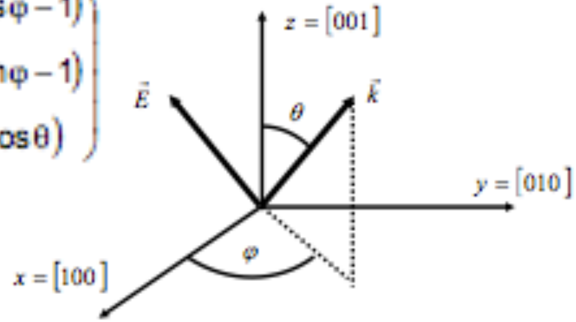
$Al_{0.3}Ga_{0.7}As$: High nonlinearity (110pm/V – 10x $LiNbO_3$) and no two-photon absorption @1.5µm
AlOx/AlGaAs high index contrast → phase-matching



GaAs $\chi^{(2)}$ Tensor $\bar{4}3m$ **(Zinc blend)**

$$\begin{pmatrix} P_x^{NL} \\ P_y^{NL} \\ P_z^{NL} \end{pmatrix} = \varepsilon_0 \begin{bmatrix} 0 & 0 & 0 & d & 0 & 0 \\ 0 & 0 & 0 & 0 & d & 0 \\ 0 & 0 & 0 & 0 & 0 & d \end{bmatrix} \begin{pmatrix} E_x^2 \\ E_y^2 \\ E_z^2 \\ 2E_yE_z \\ 2E_xE_z \\ 2E_xE_y \end{pmatrix}$$

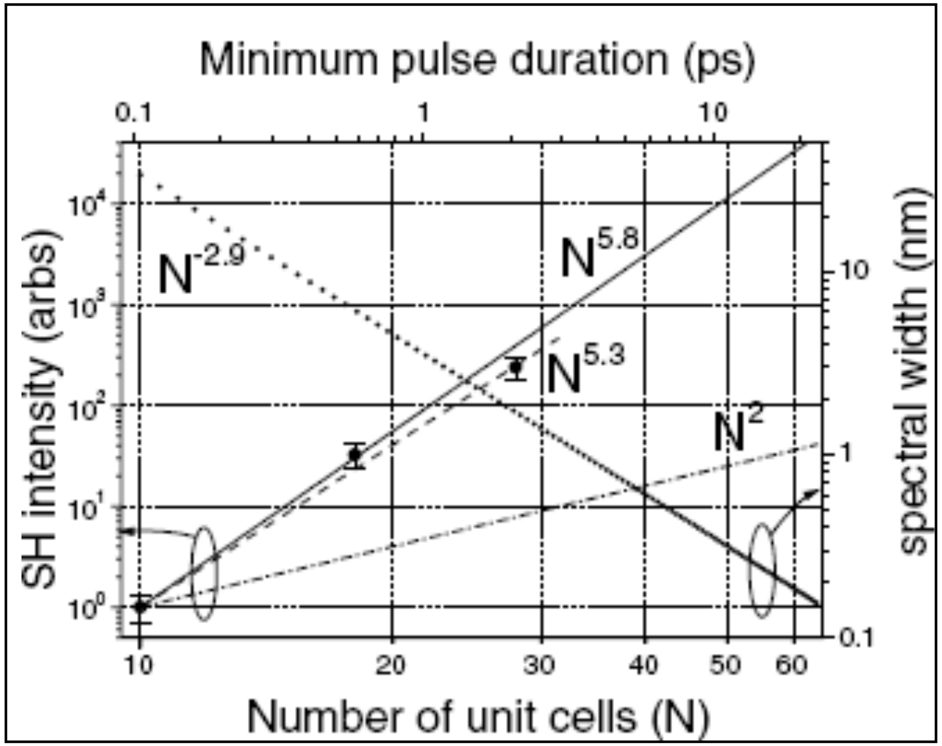
$$\vec{P}_{NL}^{\perp} = \varepsilon_0 d_{14} E_0^2 \begin{pmatrix} \sin 2\theta \sin\varphi (\sin\theta \cos\varphi - 1) \\ \sin 2\theta \cos\varphi (\sin\theta \sin\varphi - 1) \\ \cos^2\theta \sin 2\varphi (1 - \cos\theta) \end{pmatrix}$$



→ **SHG=0 @ Normal incidence!**

Second harmonic generation in Bragg mirrors

Experimental results



→ **Max efficiency = 0.1%**
→ **Efficiency goes like $N^{5.3}$**

Y. Dumeige et al, Phys. Rev. Lett. 89:043901 (2002)

→To increase efficiency we have to increase the number of layers
BUT: limitation of the growth and processing (strain, oxidation)

SOLUTION: Planar structure

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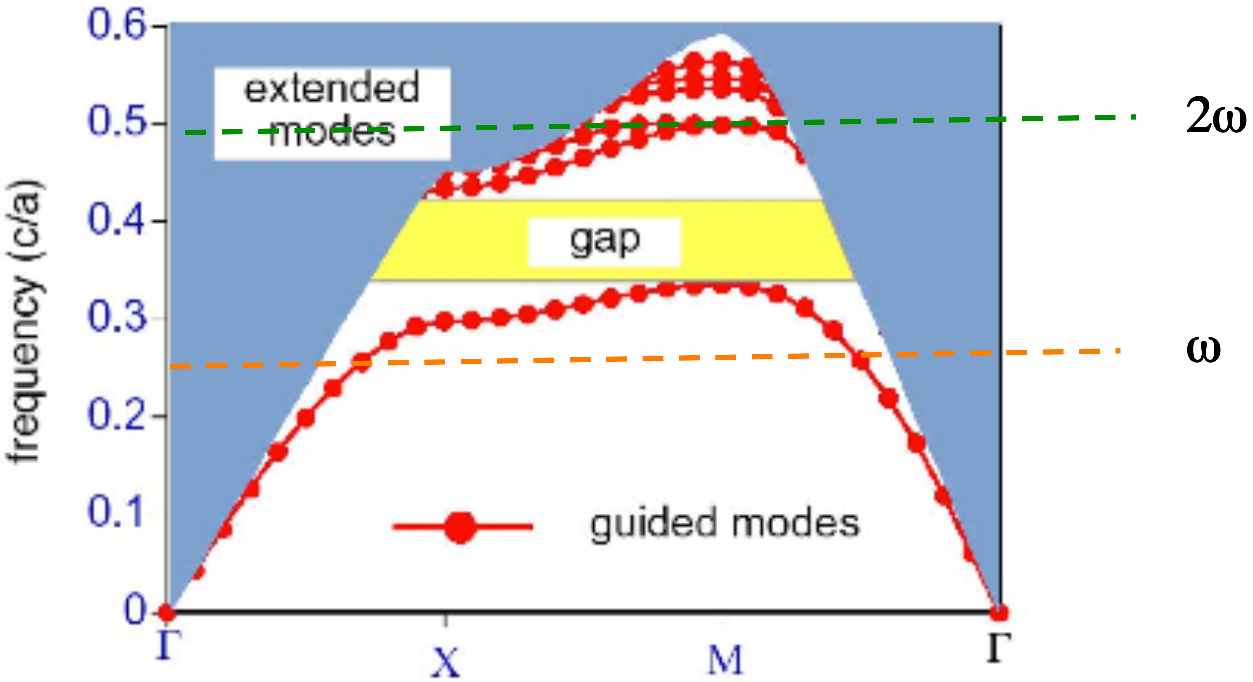
Second harmonic generation Planar 2D PhC

Use 2D structuration to obtain phase matching

Remember that we live in a 3D world → problem of leaky modes @ 2ω



→ Find a structure with phasematching and perfect confinement of the light at both frequencies

Second harmonic generation Planar 2D PhC

Defect structures don't work:
-2ω has to be TM polarised because of the form of the nonlinear tensor → small bangap
-2ω is always above the light line

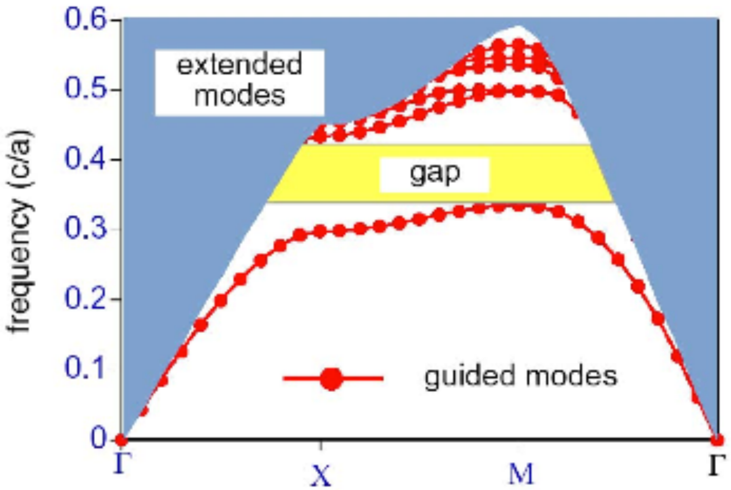
Perfectly periodic structure
- Phase matching is possible
- Field confinement in the transverse direction? Spatial walk-off?

SOLUTION: Use Non diffractive propagation in 2D PhC

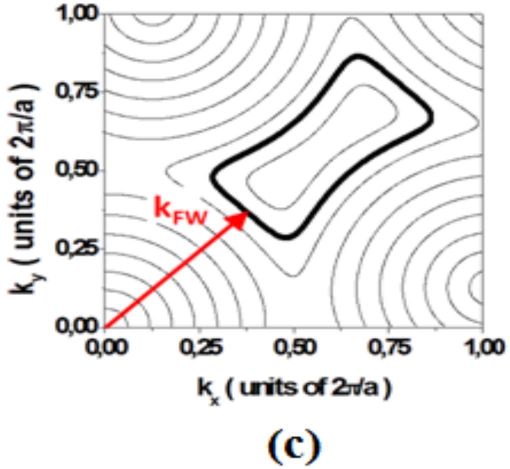
Collaboration with UPC in Barcelona (C. Nistor, C. Cojocaru, J. Trull, K. Staliunas)

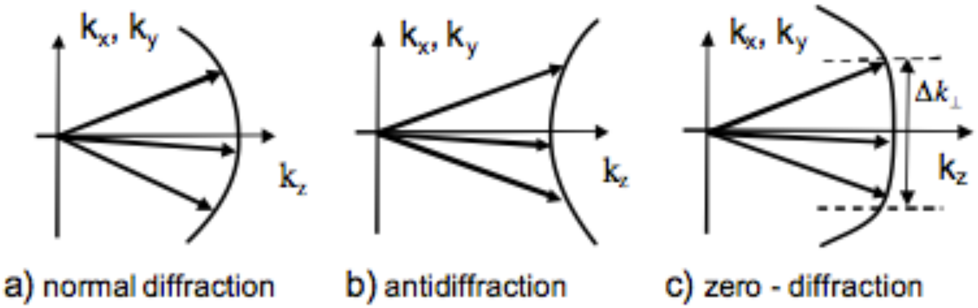
Second harmonic generation Planar 2D PhC

Non diffractive propagation in 2D PhC



isofrequency

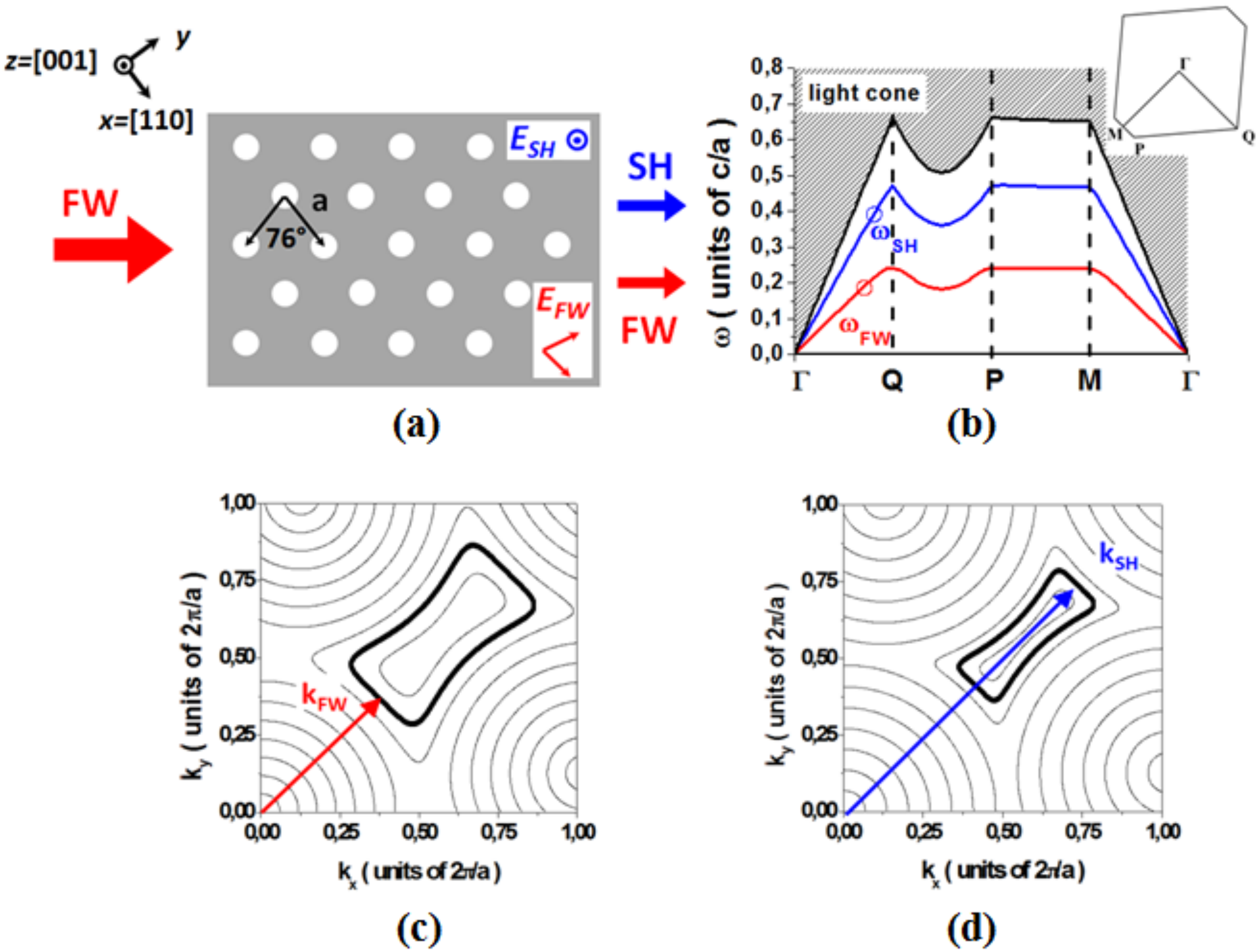




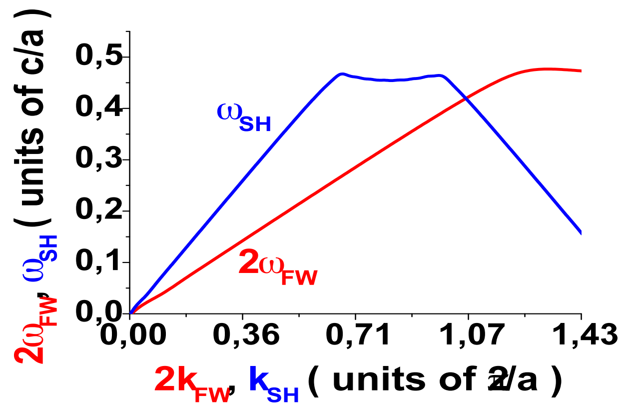
Flat band → non diffractive propagation

Second harmonic generation Planar 2D PhC

Particular configuration: Orthorombic lattice of holes



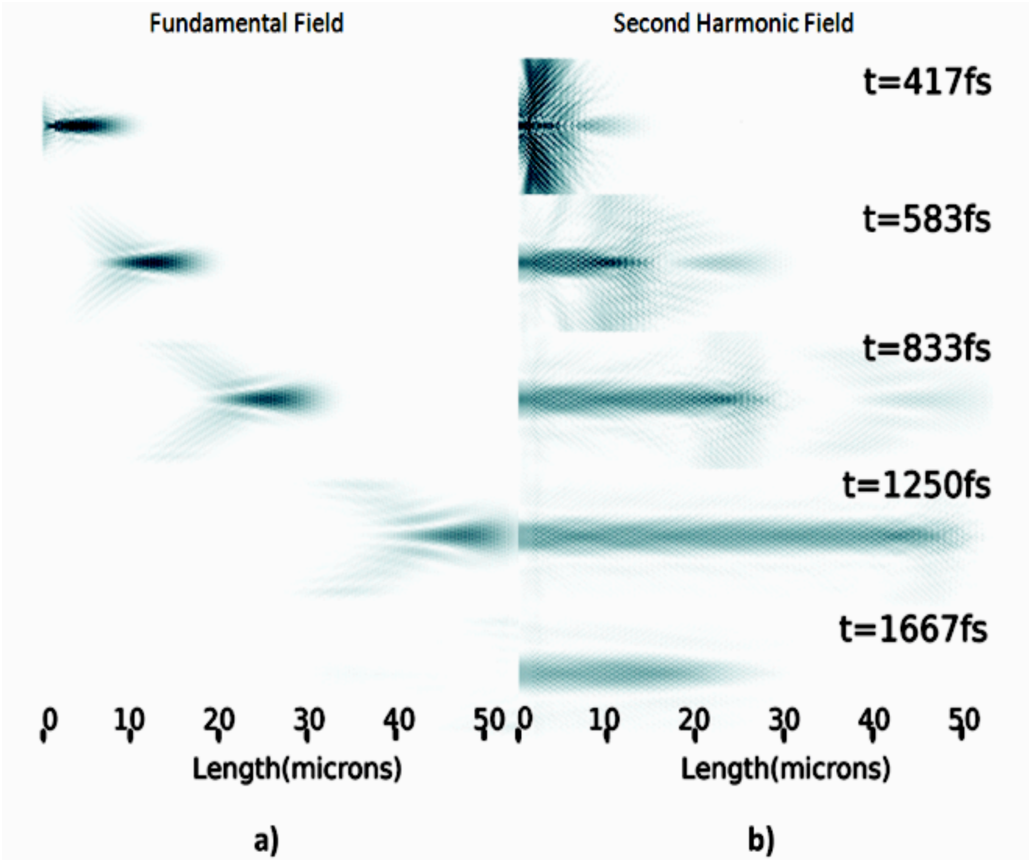
Phase matching Condition



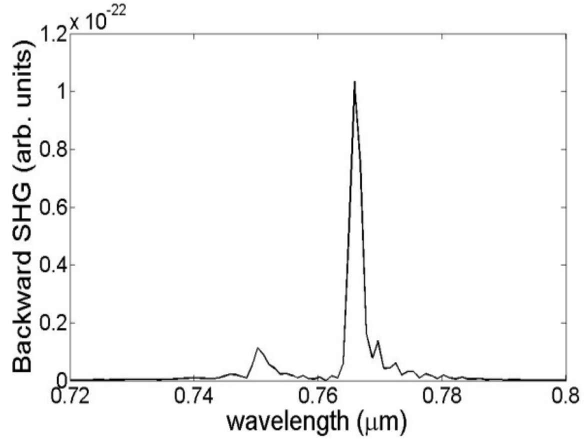
Second harmonic generation Planar 2D PhC

Numerical simulations: 2D Nonlinear FDTD

Pulsed Regime



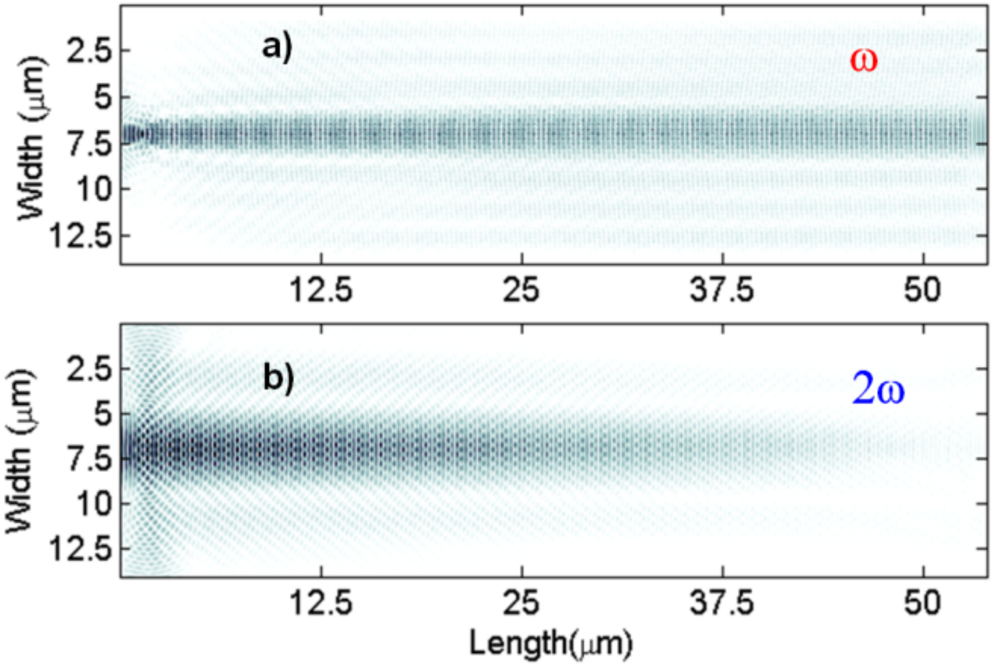
Generated SH



Second harmonic generation Planar 2D PhC

Numerical simulations: 2D Nonlinear FDTD

CW Regime



submitted to Phys. Rev. A

→SH Efficiency grows quadratically with the length → Phase matching
→ SH is generated backward (like in NIMs)
→ Non diffractive propagation both @ ω and 2ω
→ efficiency around 0.01% for 1GW/cm² for a 50 micron long structure

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NONLINEAR PHOTONIC CRYSTALS

1- Ultracompact wavelength converter

2- All-optical ultrafast switching

→ nonlinear nanocavity

3- Solitons propagation

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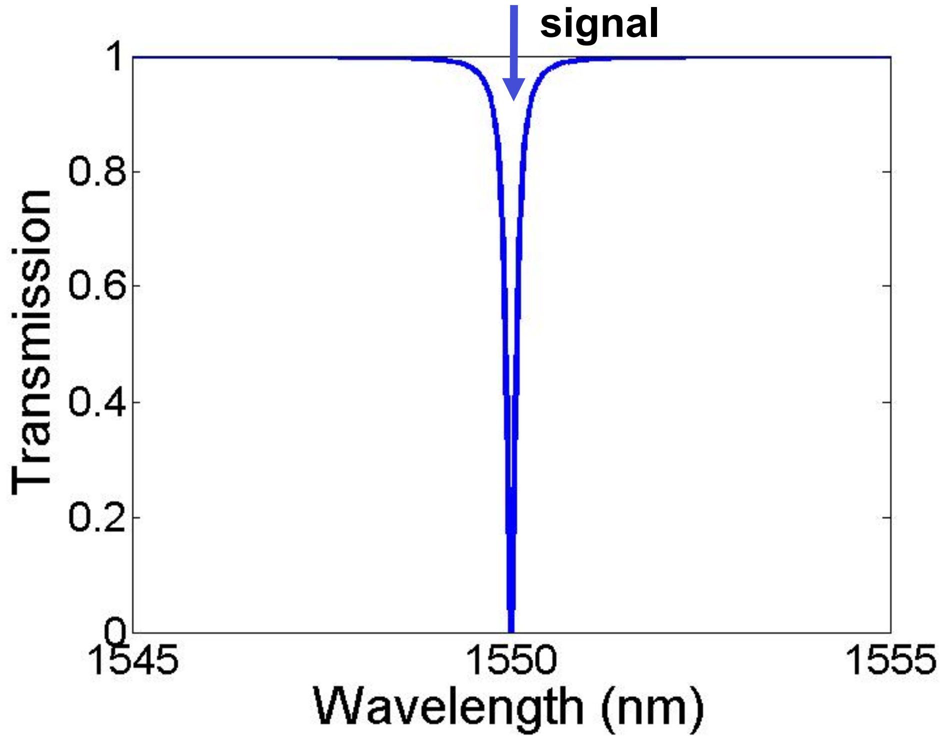
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Principle

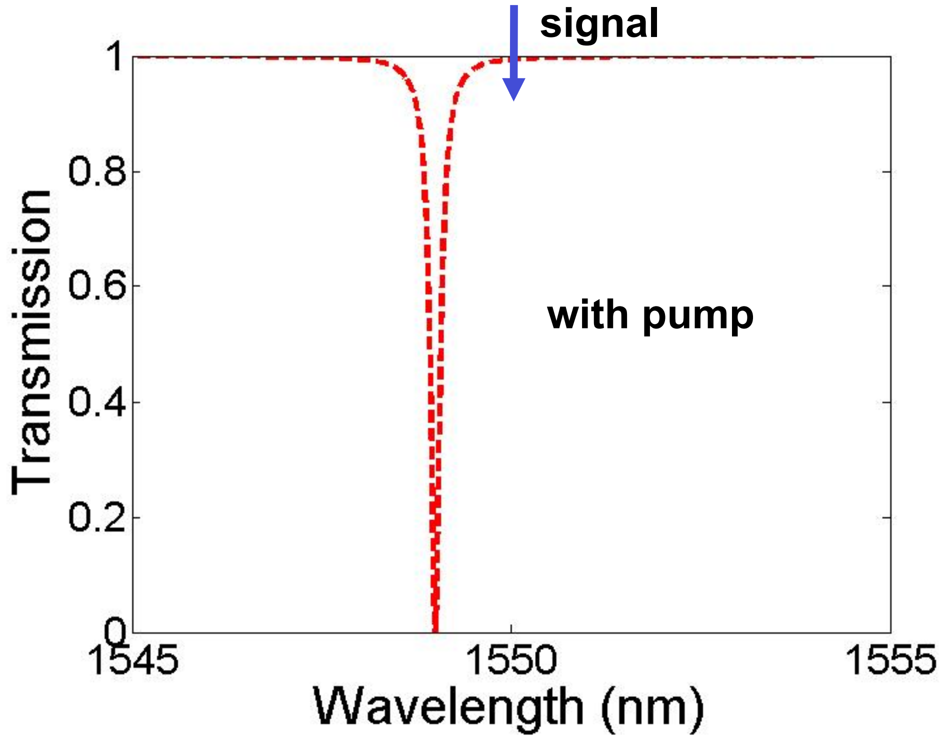
Change of refractive index through optical nonlinearity $\chi^{(3)}$



Ultrafast all-optical switching

Principle

Change of refractive index through optical nonlinearity $\chi(3)$



wavelength shift of the cavity resonance

→ change of the signal transmission

Origin of nonlinearity

A lot of physical effect lead to the dependence of the refractive index with the field intensity. One can distinguish:

- Intrinsic nonlinearity

Light interacts with the electron cloud: no "real" energy exchange between light and matter

→transparent materials

→instantaneous

→ nonlinear refractive index $n_2=2.7 .10^{-16}$ cm^2/W (for silica – x100 for Si)

- Dynamic nonlinearity

Light exchange energy with the matter. For example, thermal effects, absorption and refractive index change linked to carrier density

→energy dissipation

→ not instantaneous, depend on the dynamics of relaxation of the considered effect:

Thermal effects: heat dissipation occurs in microsecond

electronic effect: linked to carrier lifetime

→ nonlinear refractive index $n_2=10^{-6}$ cm^2/W (thermal effects)

$n_2=10^{-6}$ cm^2/W (carrier density change)

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LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Origin of nonlinearity

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- Dynamic nonlinearity

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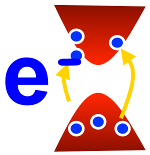
→energy dissipation
→ not instantaneous, depend on the dynamics of relaxation of the considered effect:
Thermal effects: heat dissipation occurs in microsecond
electronic effect: linked to carrier lifetime
→ nonlinear refractive index n_2=10^{-6} cm^2/W (thermal effects)
n_2=10^{-6} cm^2/W (carrier density change)

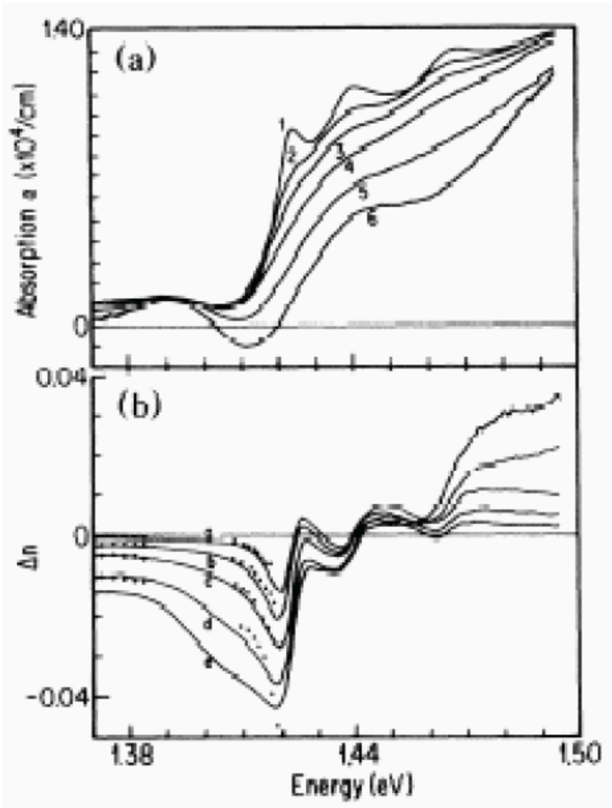
Operation based on active material

III-V quantum wells are embedded as active medium



Large optical nonlinearities through injection of carriers

***n* and α (or g) are dependent on intensity**



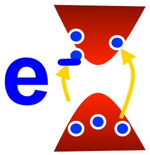
MQW in GaAs

S.W. Koch et al, J. Appl. Phys. 63 R1 (1988).

→ choice of operation wavelength determines the privileged effect

Operation based on active material

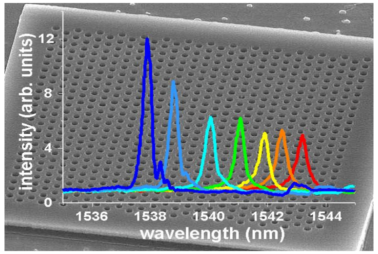
III-V quantum wells are embedded as active medium

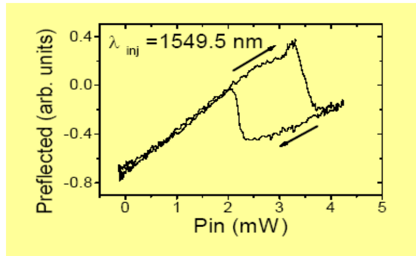


Large optical nonlinearities through injection of carriers

n **and α (or g) are dependent on intensity**

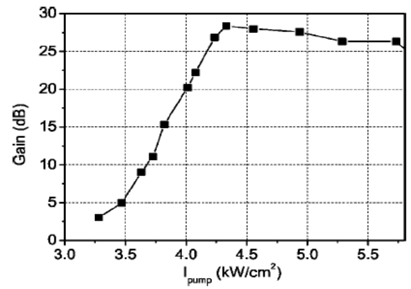
λ in the tail of absorption
dispersive nonlinearity
optical switching, bistability





F. Raineri et al, Opt. Lett. 30, 64 (2005)

λ @ max of absorption/gain
absorption/gain nonlinearity
amplification, laser emission, bistability



F. Raineri et al, Appl. Phys. Lett. 86, 091111 (2005)

What are the issues?

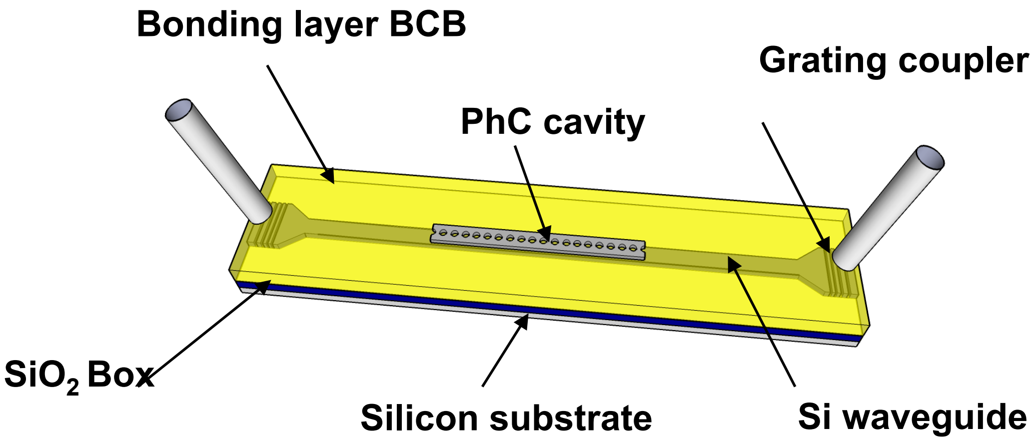
- **Having a large nonlinear response:**

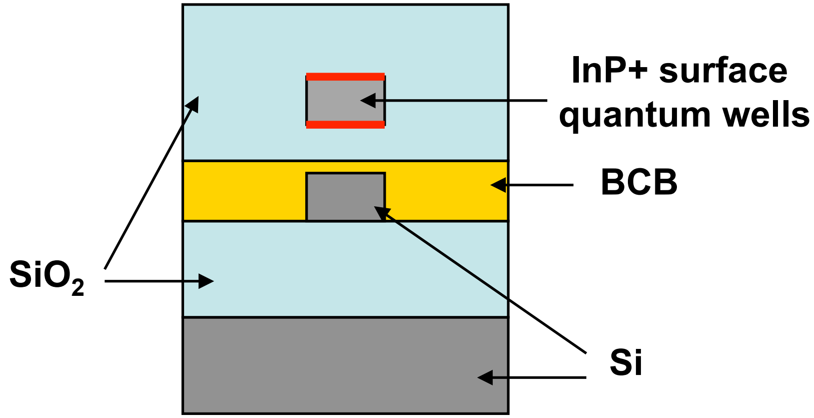
→ Dynamic nonlinearities
→ High Q cavity mode and small volume for:
- large extinction ratio
- higher pump intensity (can be different mode)

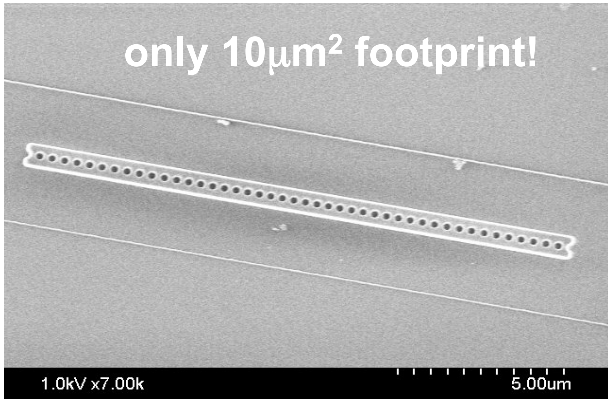
- **Having fast response:**
→ engineering of carrier lifetime

- **Avoiding thermal effects** which induces slow dynamics and material degradation
→ engineering of thermal resistance (no suspended membranes!)

Reduction of carrier lifetime using surface InGaAs QW and material patterning





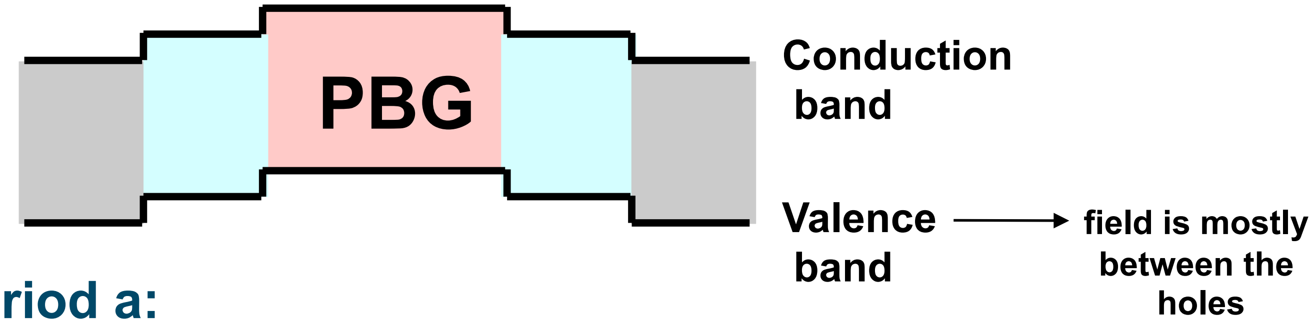


Fully embedded in SiO_2 for robustness and increased heat sinking

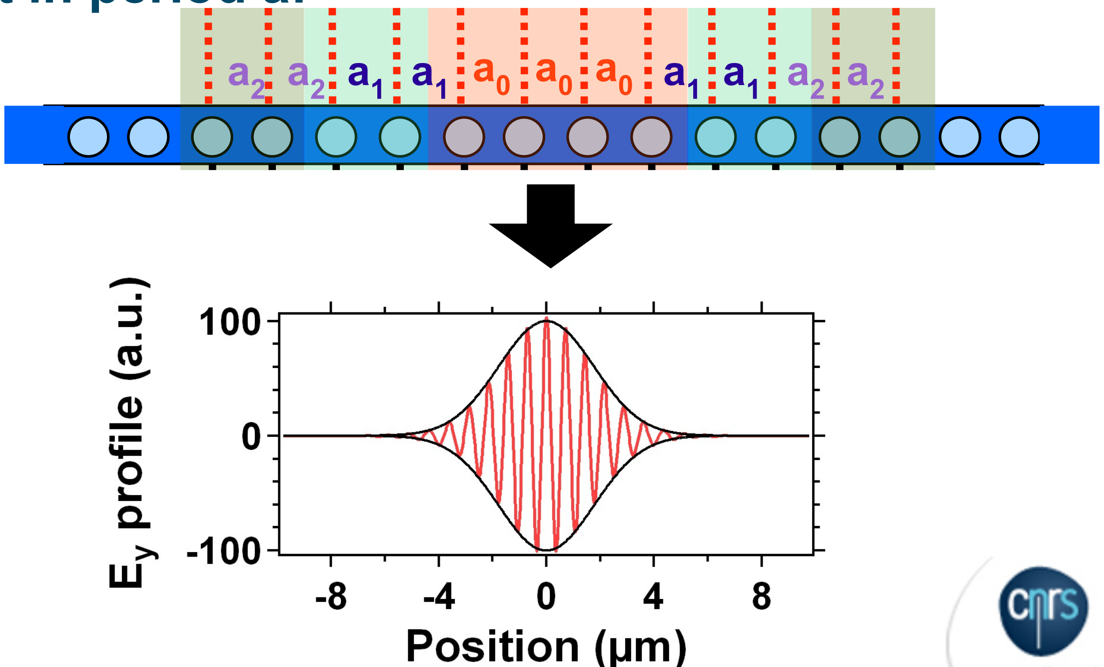
(thermal resistance 10x smaller than suspended membrane)

High-Q design of PhC cavity

- Apodized cavity concept: profile of the field envelop designed to suppress radiation losses. **(See Tanaka *et al* Journal of Quantum Electronics, 26, 11 (2008))**

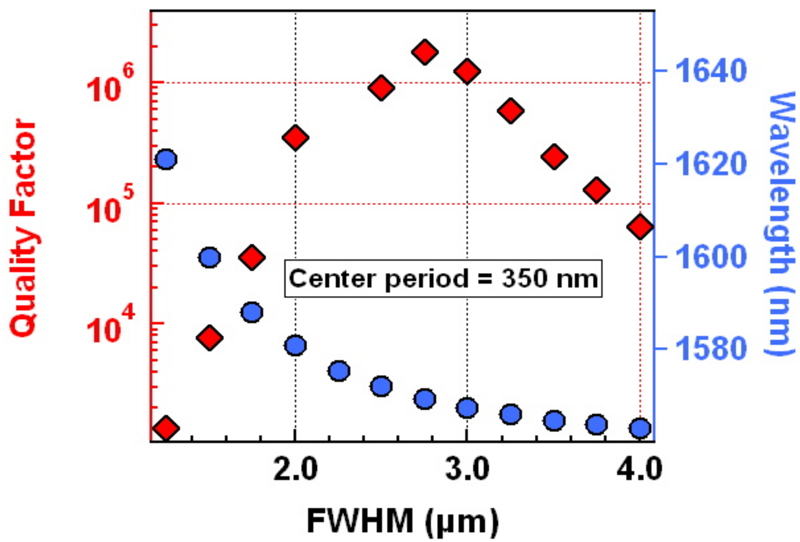


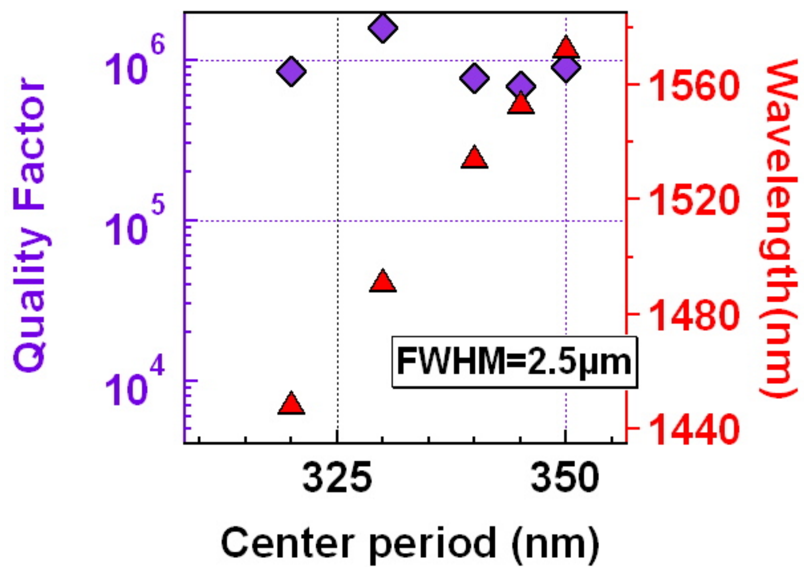
- Progressive shift in period a:

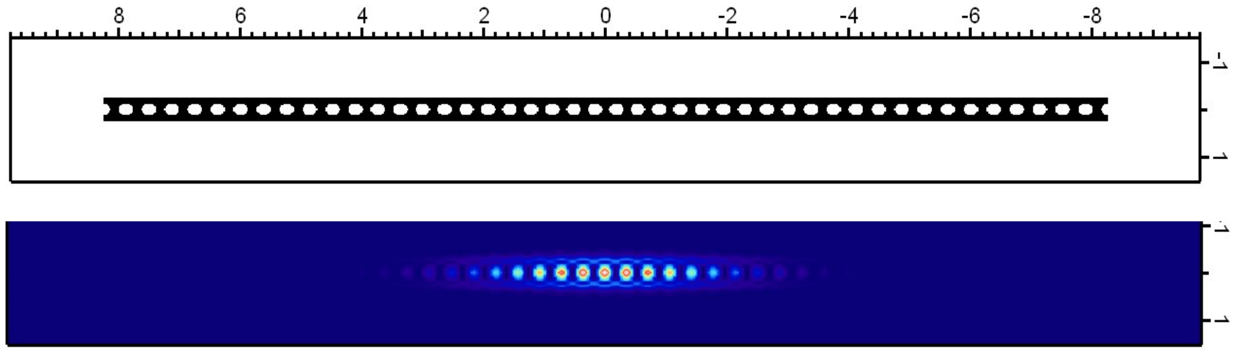


High-Q of encapsulated Wire Apodized Cavity

3D FDTD calculations







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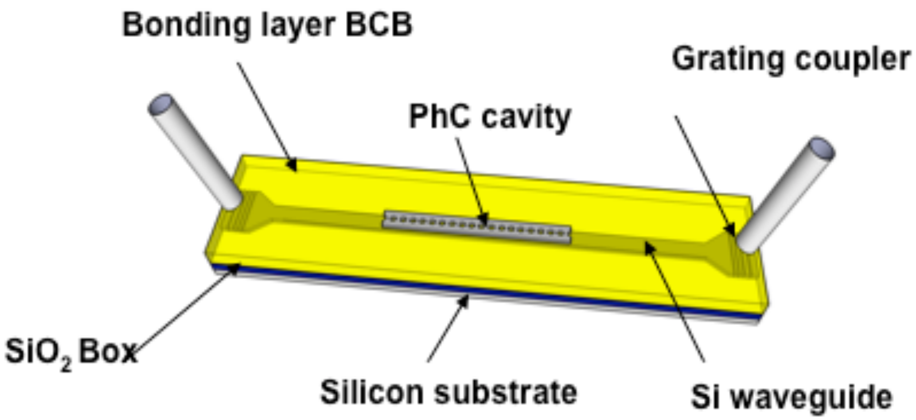
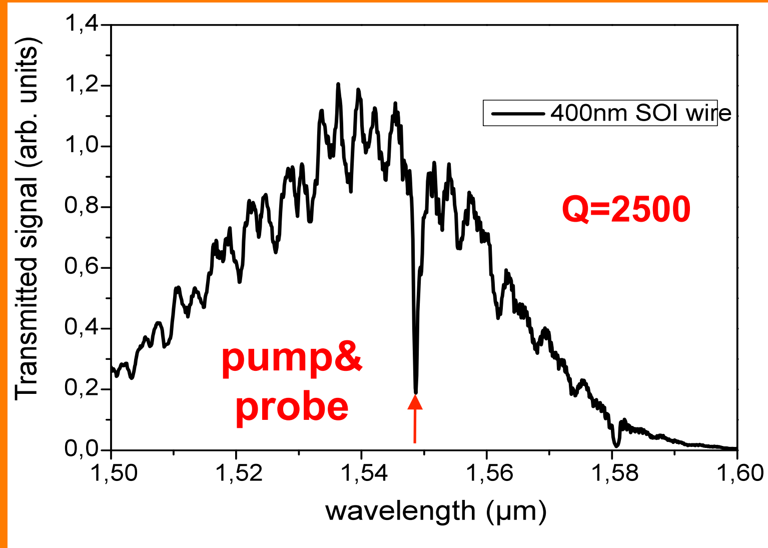
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Ultrafast switching



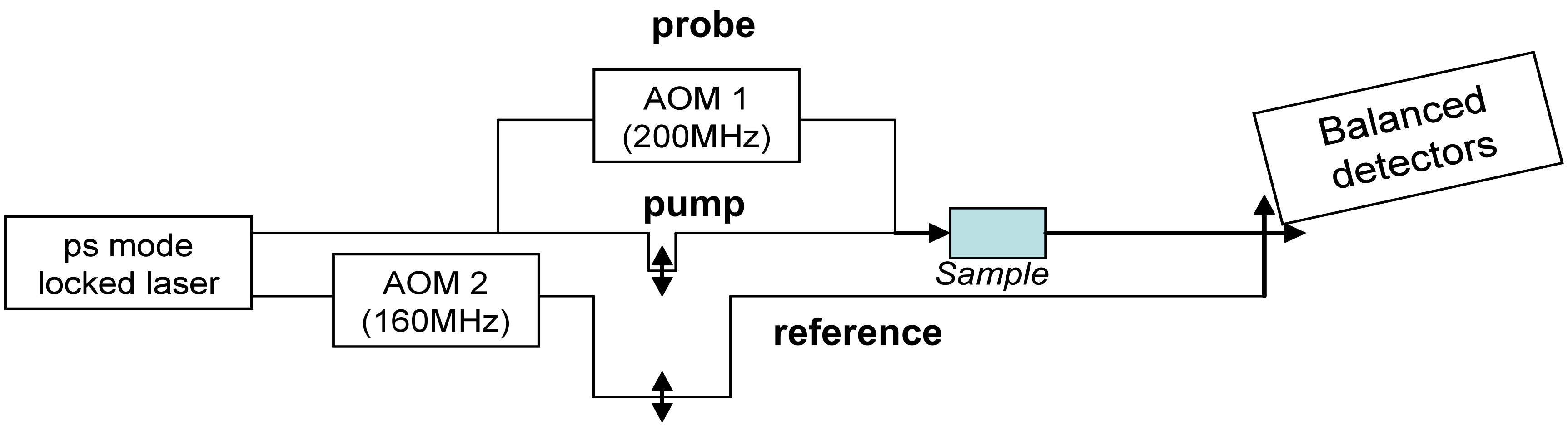
→ **sharp resonance for switching**

Transmission characterisation



→ induced blue shift of the resonant by the pump

Quasi degenerate pump-probe experiment with balanced heterodyne detection

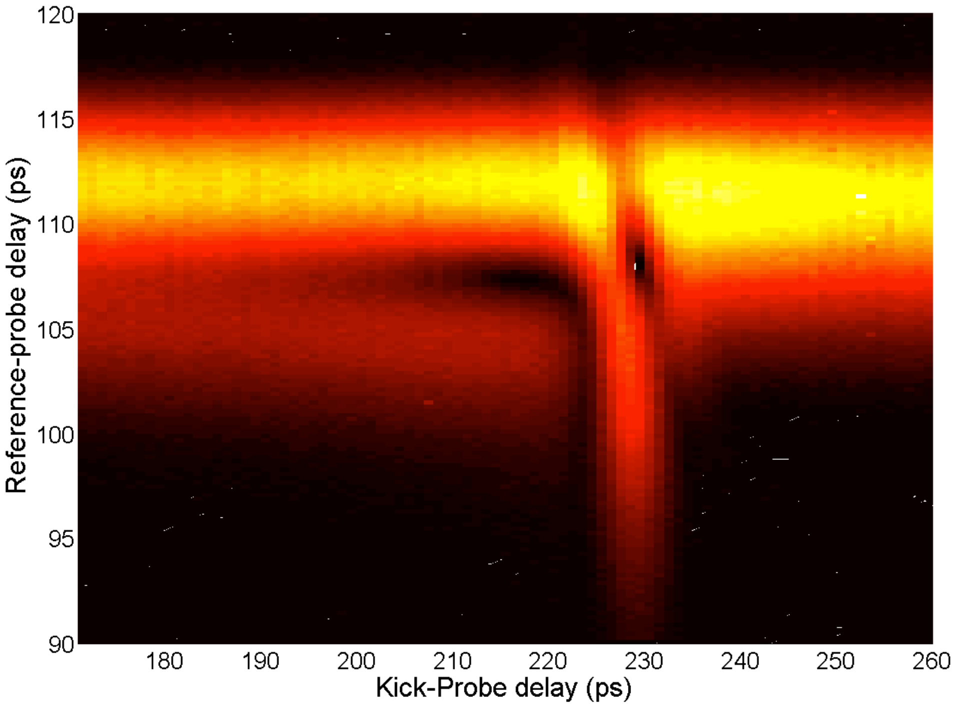


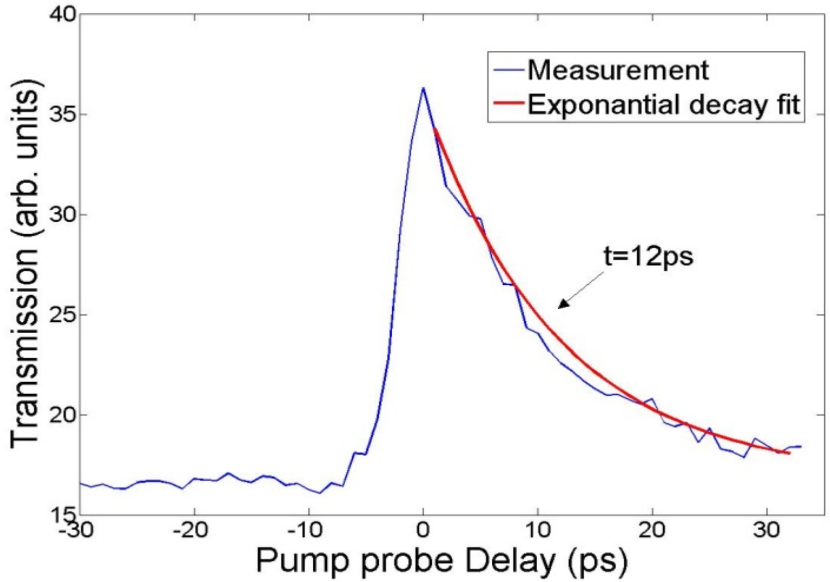
Detection of signal at the beat frequency of probe and reference as a function of the delays

→ we don't detect the pump
→ using a powerful reference we increase the detection sensitivity
→ we can reconstruct the signal pulse in the time domain

Ultrafast switching

Measurements





→ 12 ps carrier lifetime!

→ Switching energy of 40fJ!

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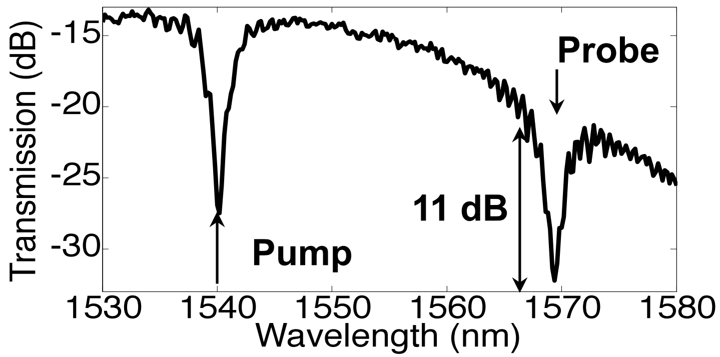
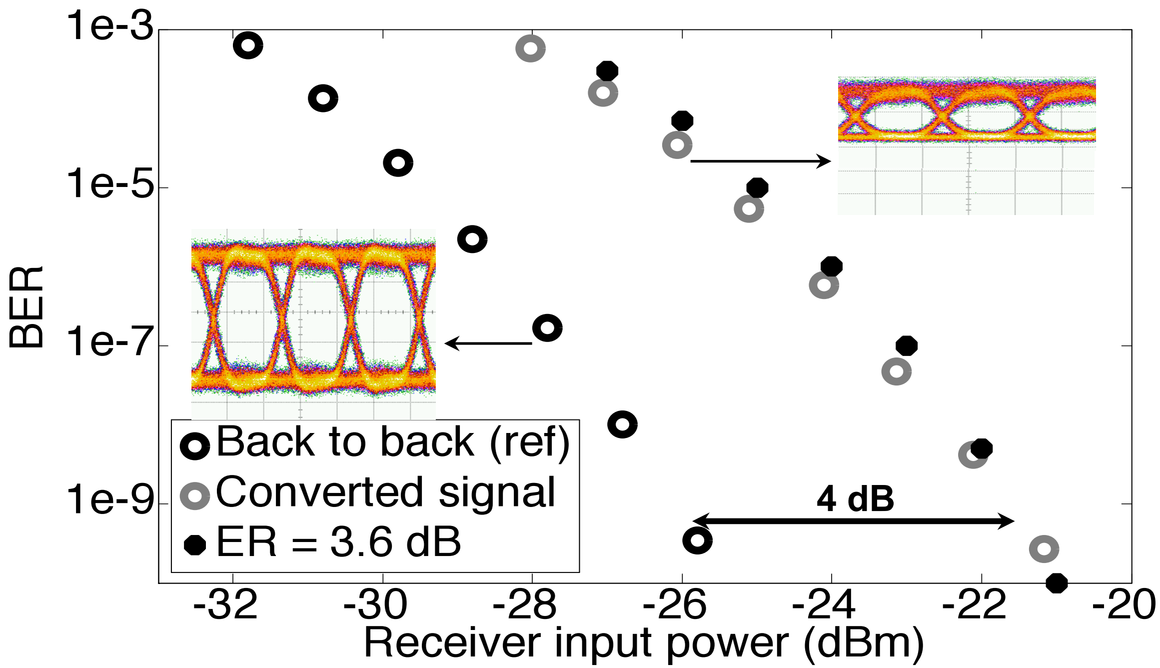
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

10Gbits/s Wavelength conversion

Measured @ Foton by K. Lengle, M. Gay, L. Bramerie, T.-N Nguyen



→ 2 colours!



→ 6 mW peak power maximum

→ Error free operation of the converted signal

(4 dB penalties coming from low extinction ratio of the converted signal)

First time ever PhC based all-optical switching @ high bit rate!

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LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

1- Ultracompact wavelength converter

2- All-optical ultrafast switching

3- Solitons propagation

→ Motivations

→ Slow light in PhC waveguides

→ Solitons propagation

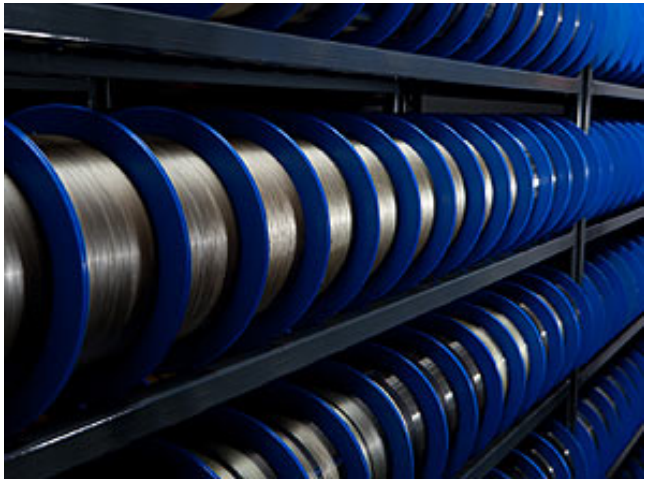
Motivations

◆ Integrated optical circuit will play a crucial role in the next generations of processors:
→ interconnections between cores
→ enhanced bandwidth
→ low power consumption

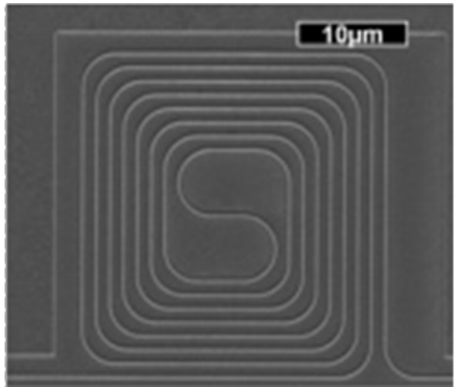
Among all the functionalities necessary, buffering and storing are of primary importance to allow network management and control latency

So why slow light?

Optical fiber



SOI wire waveguides



Losses ≈ 0.1dB/km

→ 50µs for 10km and 1dB of losses

Losses ≈ 1dB/cm

→ 100ps for 1cm and 1dB of losses

→ slow light is necessary for compact delay lines

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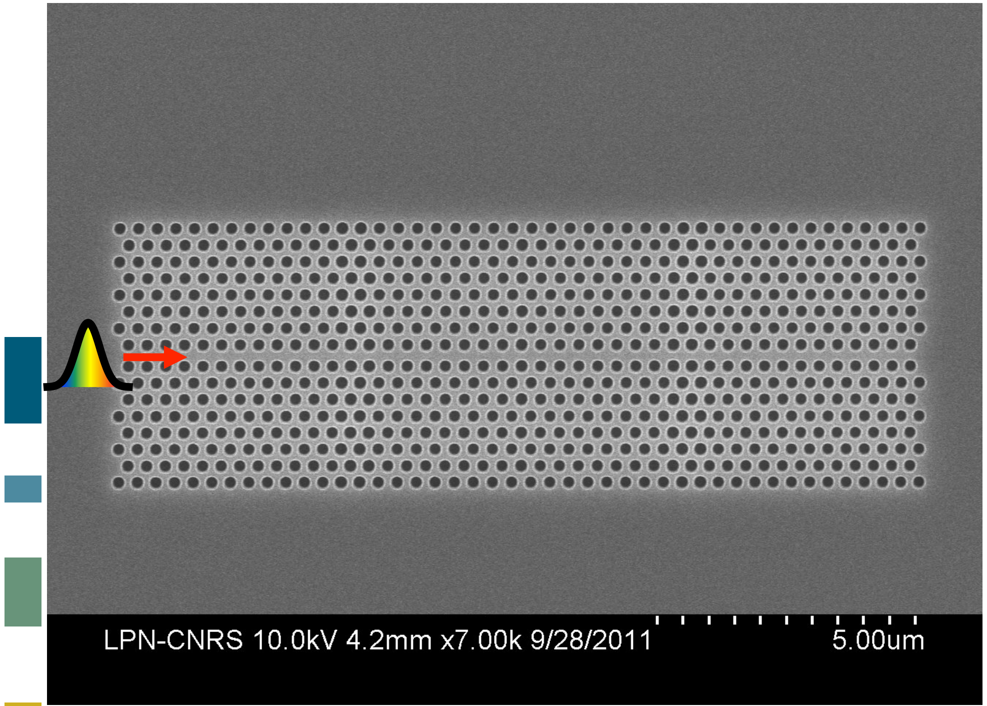
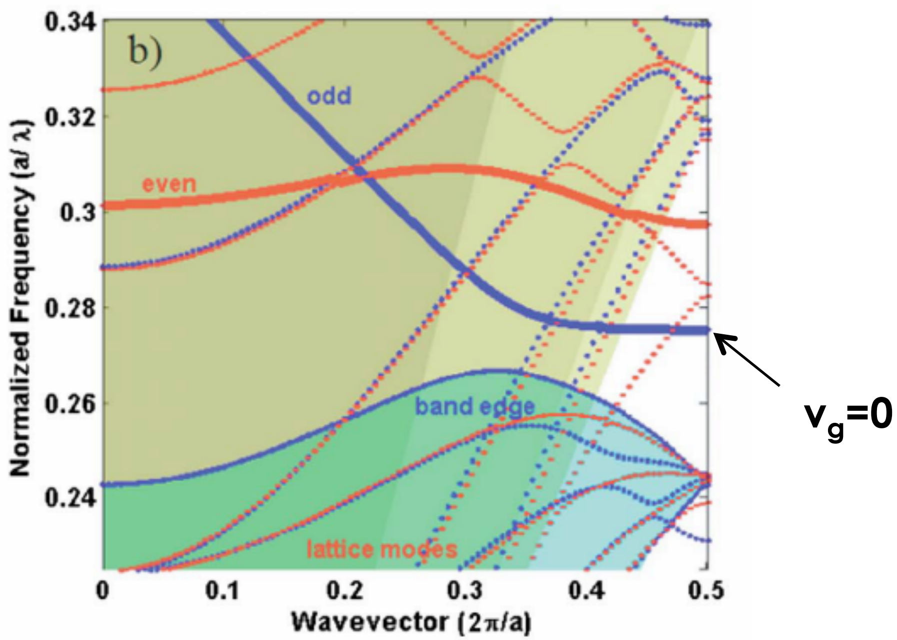
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Slow light in PhC waveguides



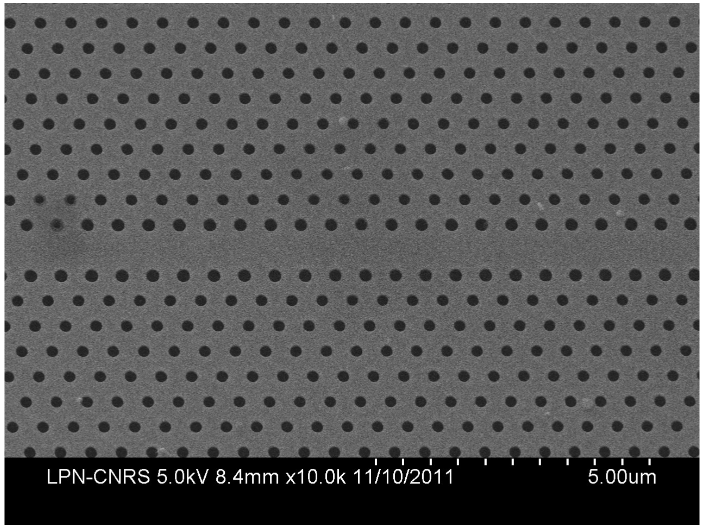


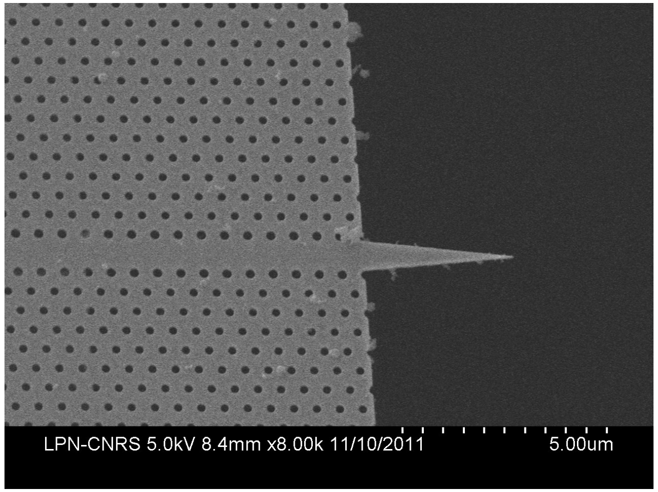
Analog to coupled resonators

M. Notomi et al, PRL 87, 253902, (2001).
H. Gersen, et al. PRL 94, 073903 (2005)
L. O'Faolain, et al. OE 15, 13129 (2007)

Studied sample

InGaP W1 waveguide





- **2 photons absorption @1.55µm avoided (InGaP bandgap @1.9ev)**
- **a=465nm – r/a=0.19**
- **dispersion adjusted with modified holes at the edge of the W1 (r/a=0.22)**
- **Tapered tip to increase coupling (N.-V.-Q. Tran et al, Appl. Phys. Lett. 95, 061105 (2009))**

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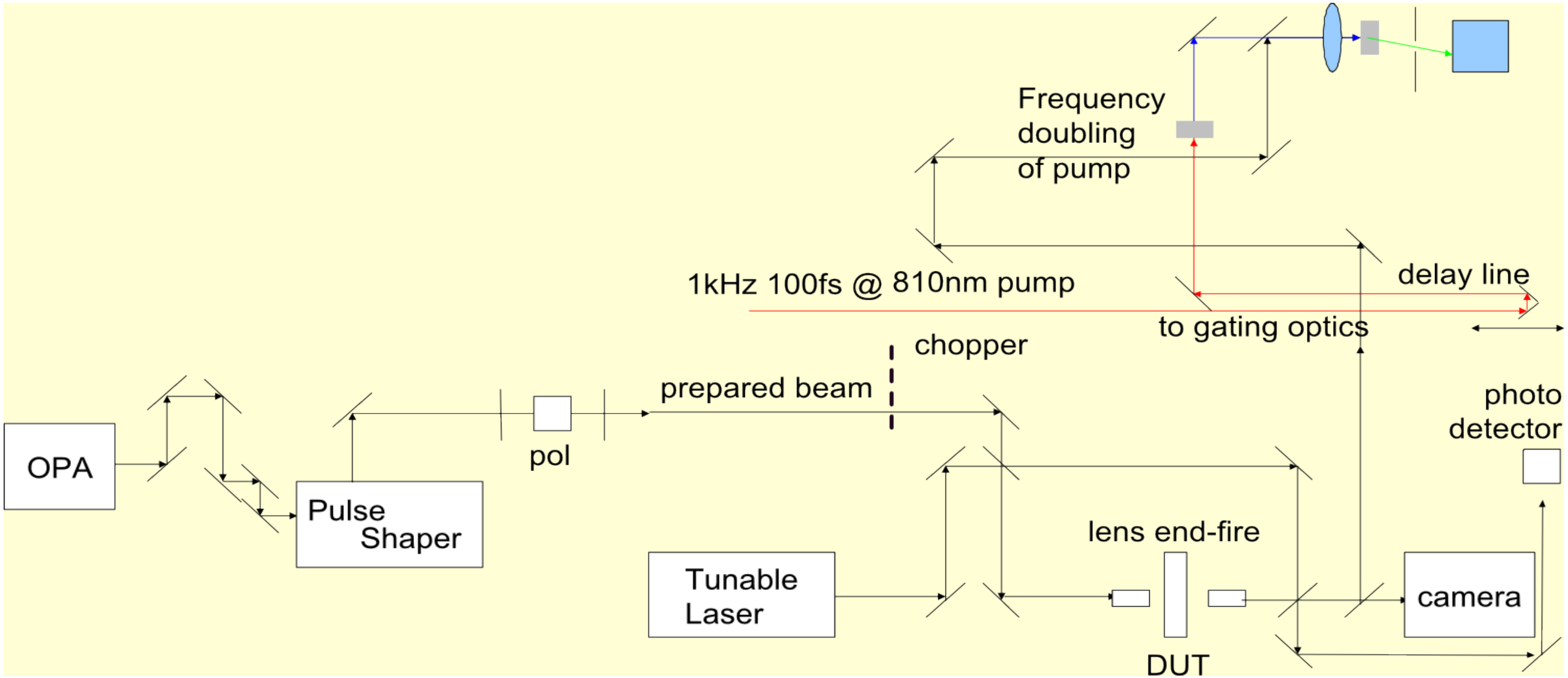
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Time domain measurements

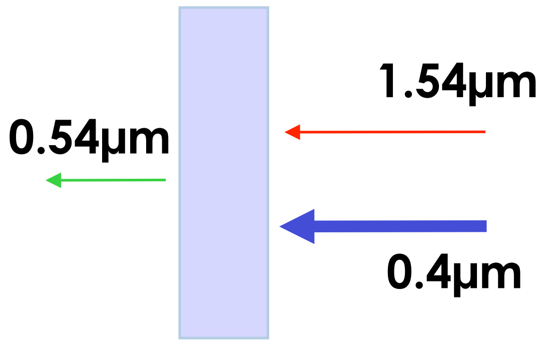
Parametric amplification accurate mapping of the temporal response of PhC devices



(F. Raineri et al, Opt. Express17, 3165)

Time domain measurements

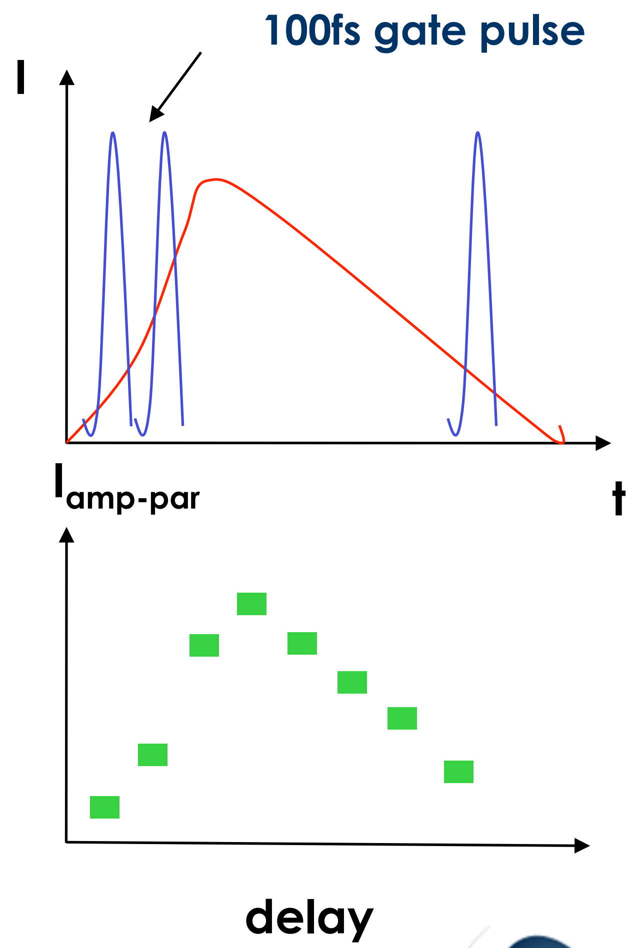
Parametric amplification = optical gating



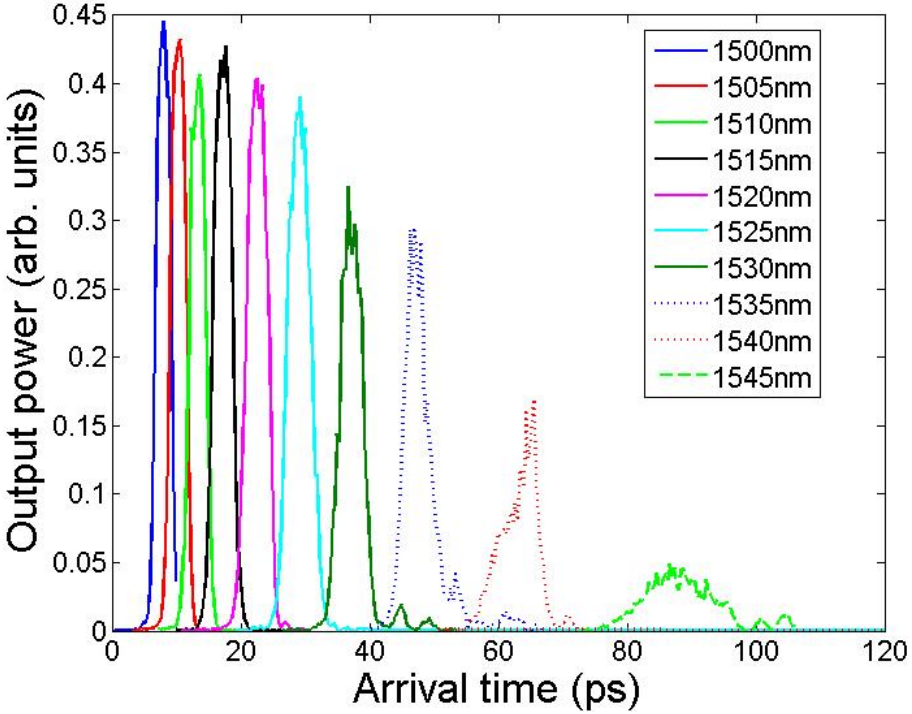
Parametric amplification in BBO

→Instantaneous

→ sensitivity<0.1fJ

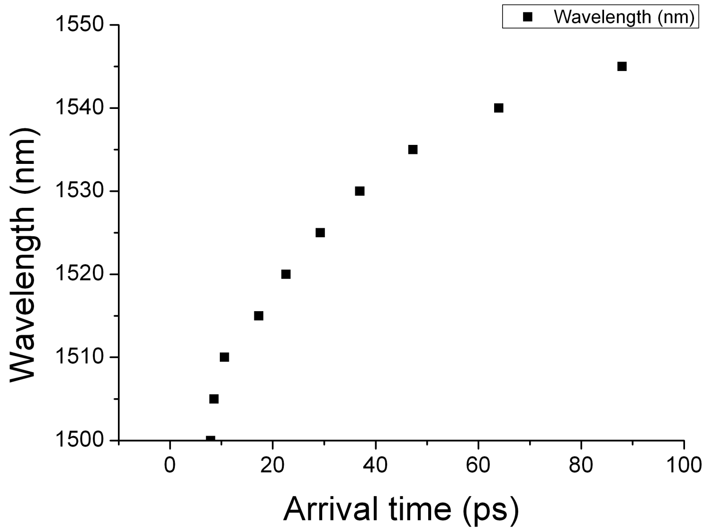


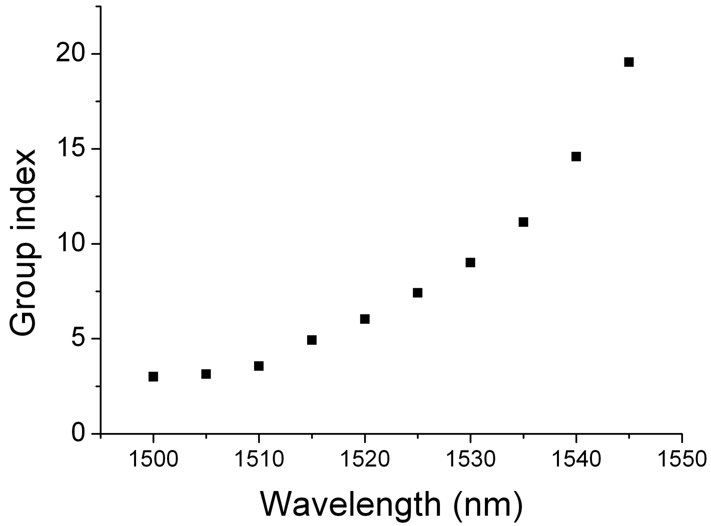
Time domain measurements



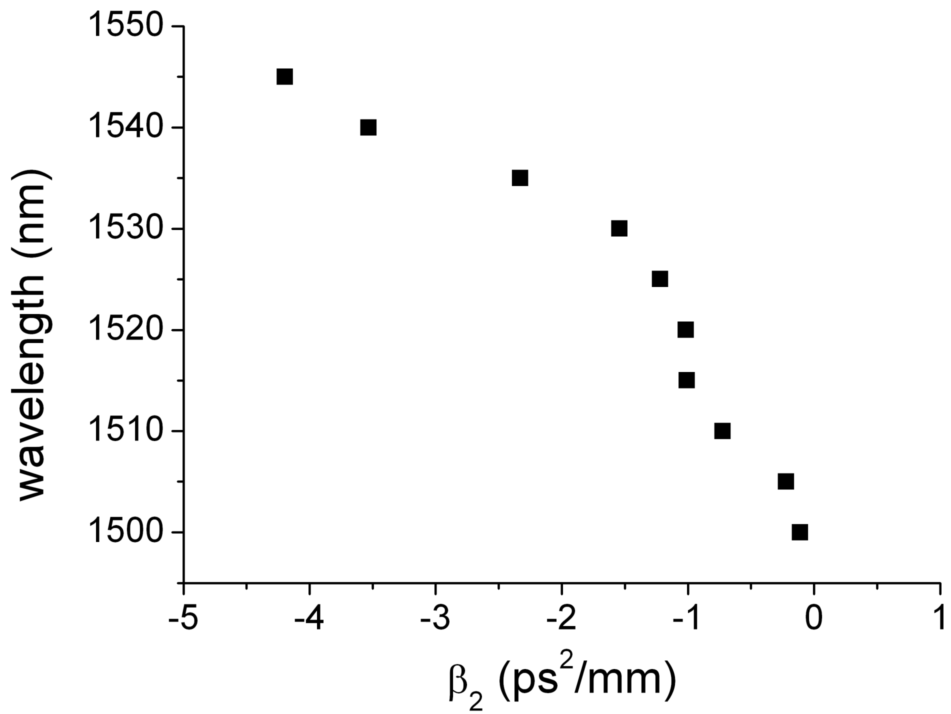
→delay up to 100ps in 1.5mm

→$v_g = c/20$ demonstrated





Problem of GVD



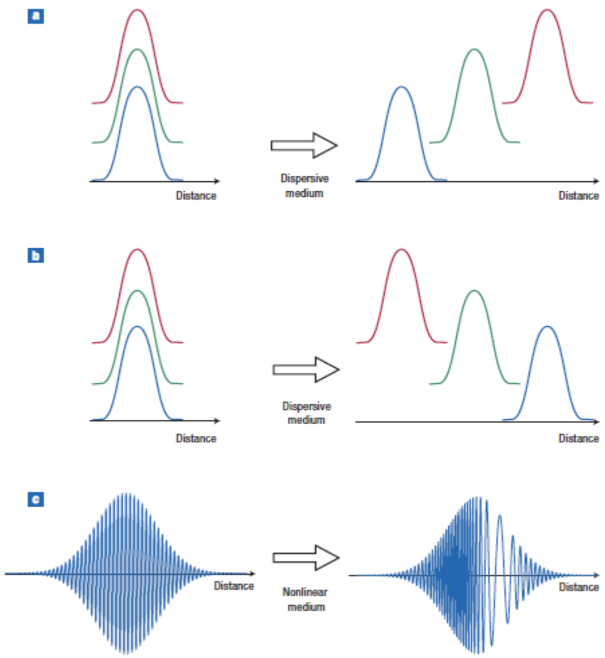
$$\beta_2 = \frac{-\lambda^2}{2\pi c}\,\frac{d\left(\frac{1}{v_g}\right)}{d\lambda}$$

→ 5.10^3 greater than in optical fibers!

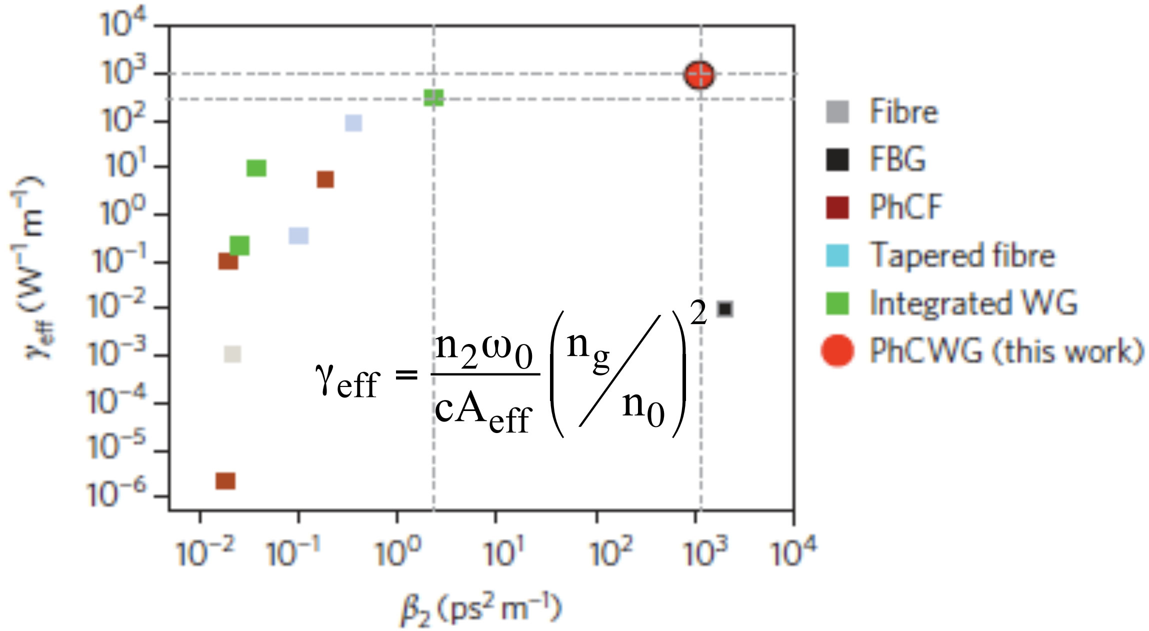
→1ps pulse stretches up to 4ps in 1.5mm for β_2=-1ps²/mm!

Kerr nonlinearity to conpensate GVD → SOLITONS

Formation of a soliton



A soliton is a pulse whose temporal broadening due to dispersion is compensated by SPM due to the nonlinearity of the medium

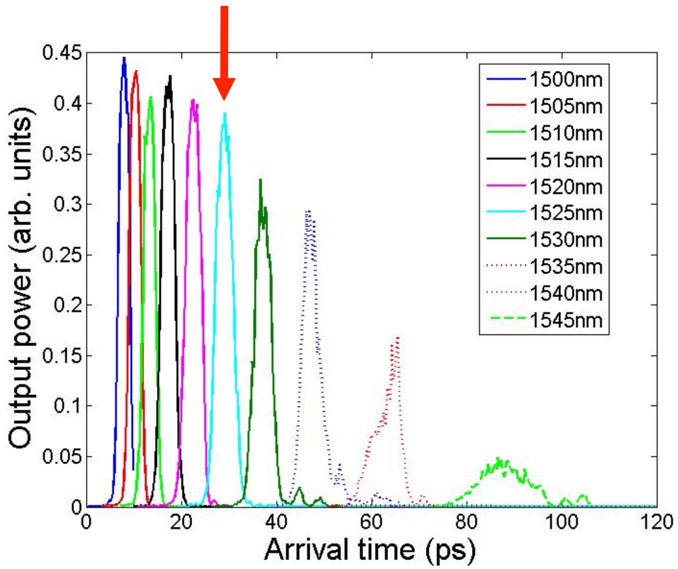


→ efficient nonlinearity with low power in InGaP PhC waveguide

Observed recently in 2DPhC waveguide using autocorrelation

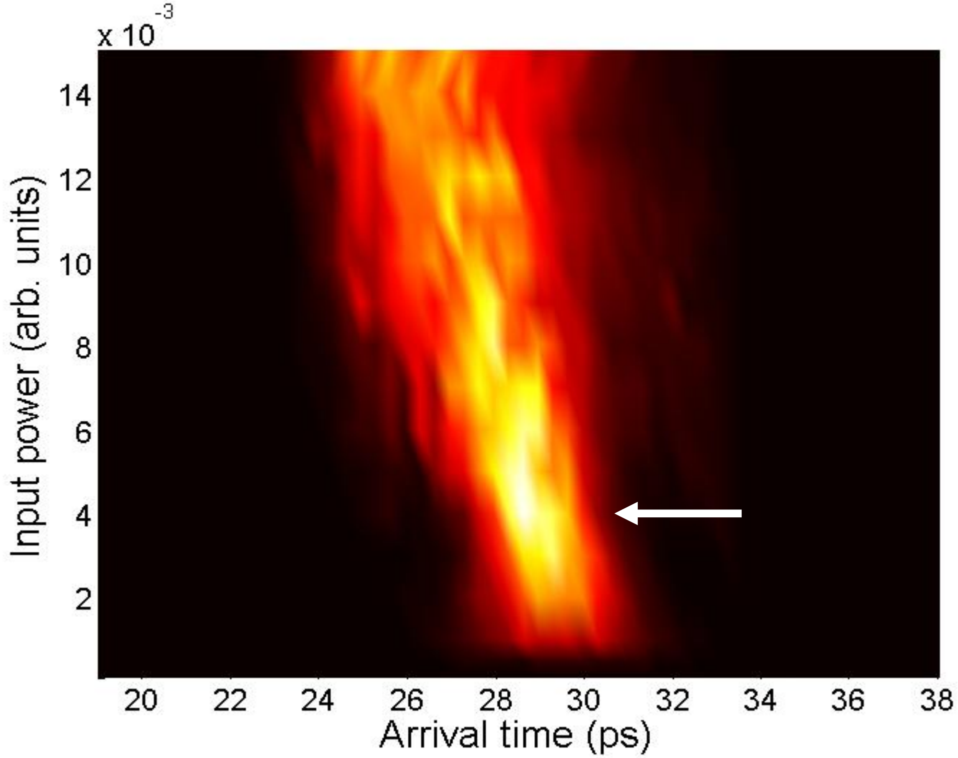
P. Colman et al, Nat. Photon 4, 862 (2010)

Time domain measurements



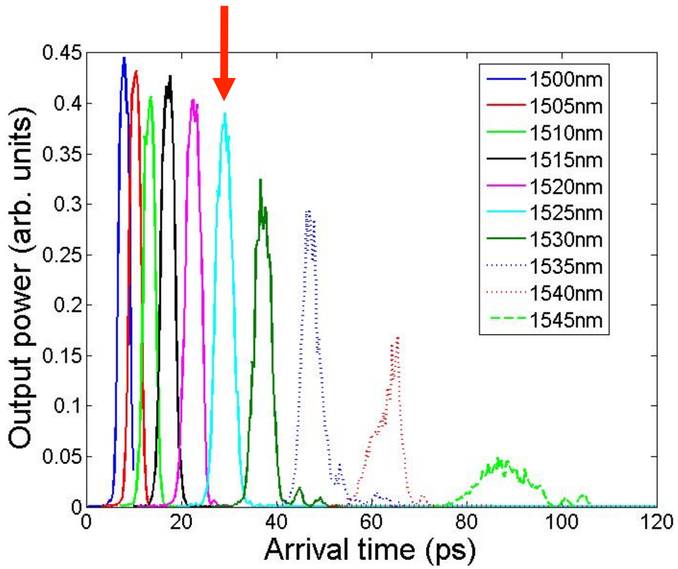
2ps Gaussian pulse@1525nm
vg=c/9

Time domain measurements vs Power



→Pulse compression and soliton formation for E_{in}=40pJ

Time domain measurements



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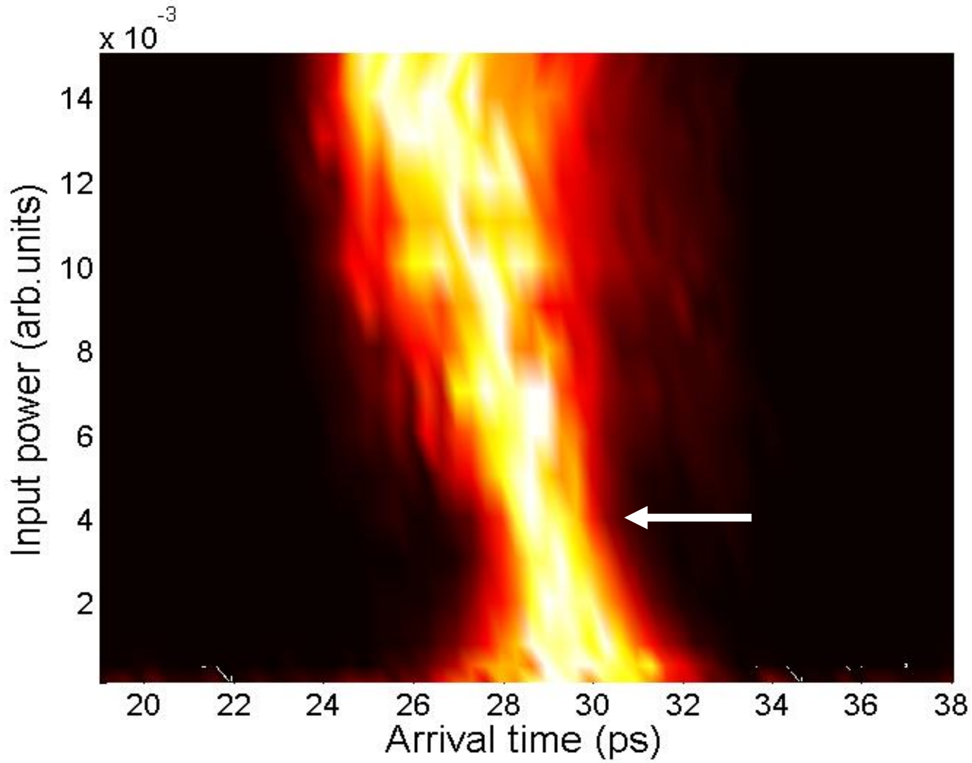

→Pulse compression and soliton formation for E_{in}=40pJ

Normalised to max power

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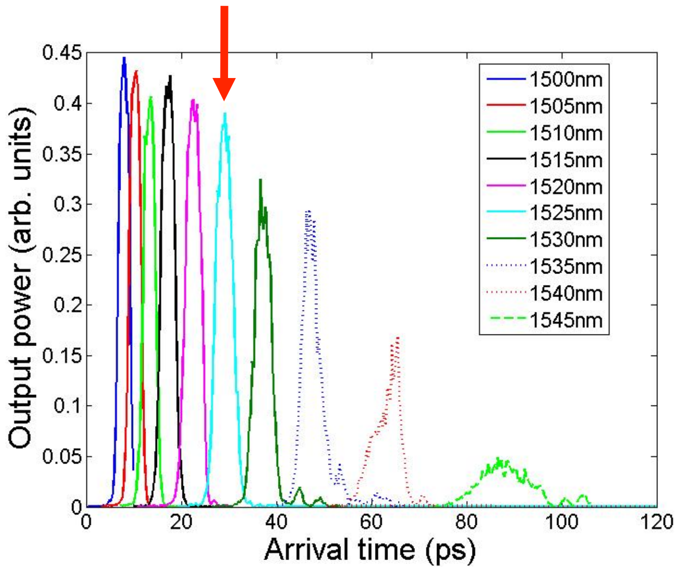
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Time domain measurements



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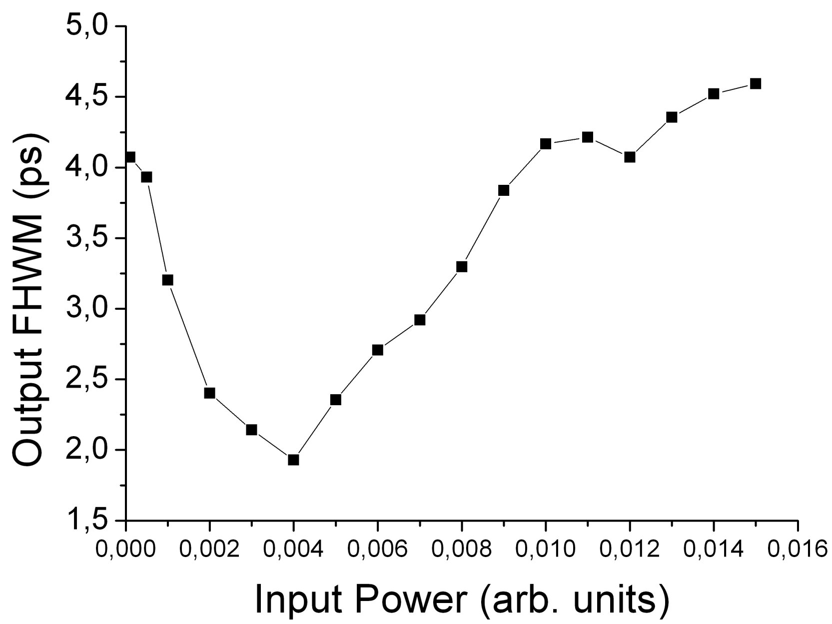

→Pulse compression and soliton formation for E_{in}=40pJ

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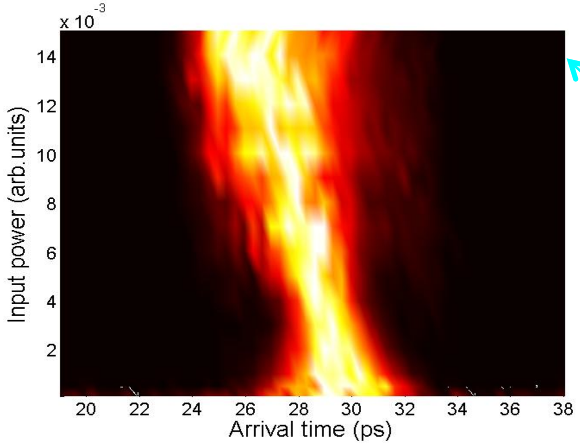
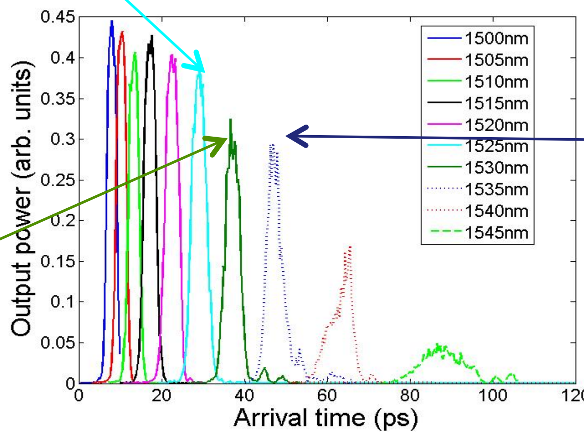
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Time domain measurements

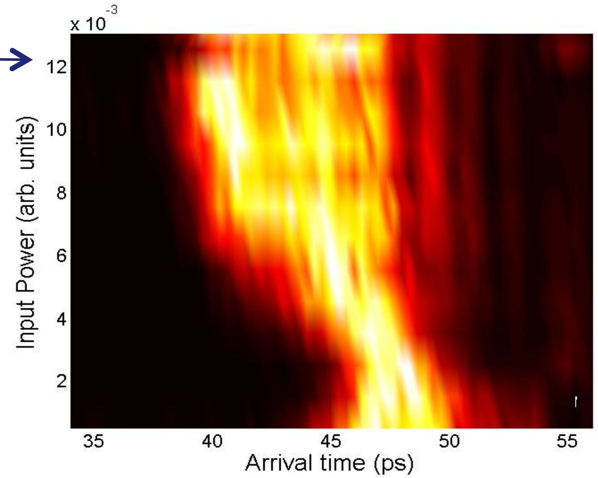
1525nm

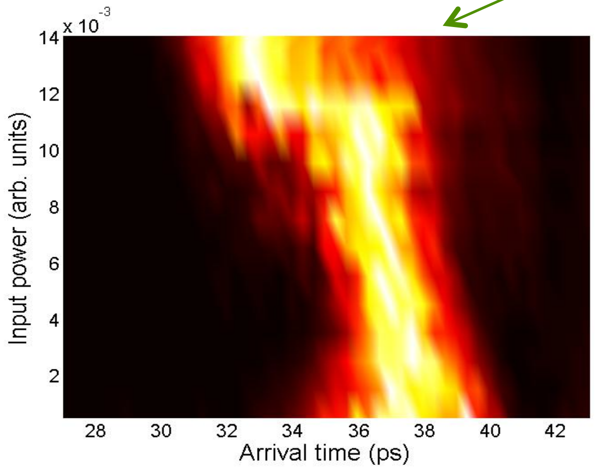
wavelength dependence





1535nm

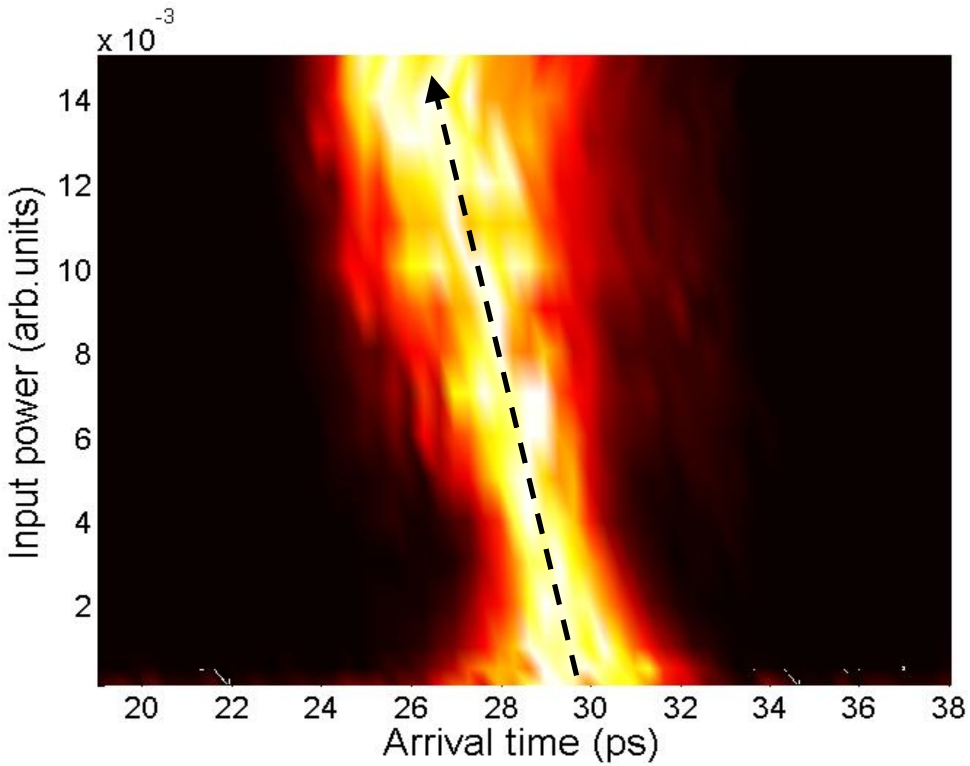




1540nm

1530nm

Pulse acceleration



linear dependence of delay with input power

→ $\Delta t/\Delta E$=-20fs/pJ

for E_{in}=100pJ

$\Delta v_g/v_g$=7%

$$\gamma_{eff} = \frac{n_2\omega_0}{cA_{eff}}\left(n_g/n_0\right)^2$$

This is attributed to:

- dependence of the effective nonlinearity with v_g – not negligible in PhC case

- slow mode redshifts for increasing refractive index (Kerr Effect)

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LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

1- Photonic crystal lasers: ultimate lasers?
→ How do you go about it?
→ Unique properties: static and dynamic properties

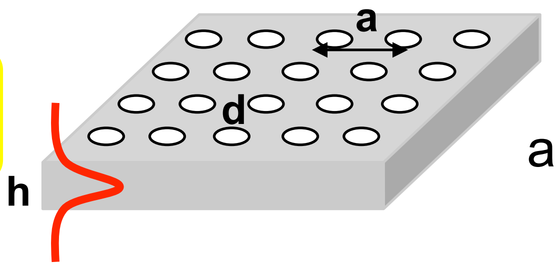
2- Ready for application? Some issues
→ Interfacing
→ Electrical injection

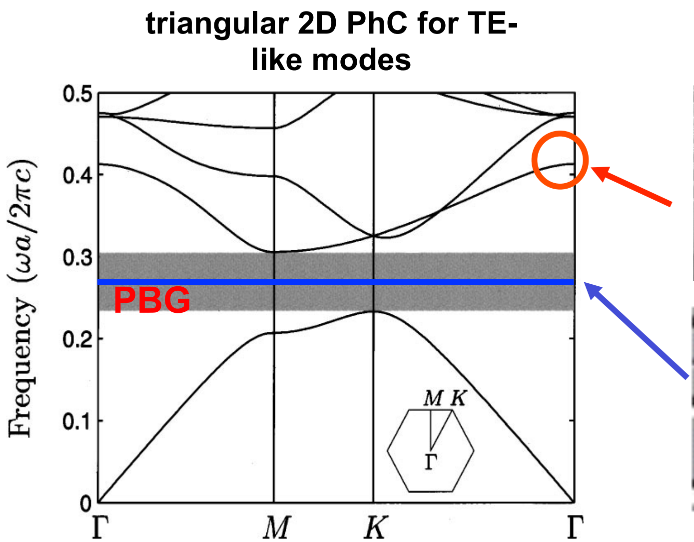
1- Photonic crystal lasers: ultimate lasers?
→ How do you go about it?
→ Unique properties: static and dynamic properties

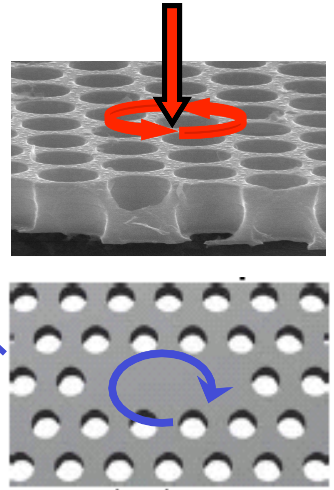
2- Ready for application? Some issues
→ Interfacing
→ Electrical injection

PhC laser: How do you go about it?

• 2D PhCs offers an extensive control on light propagation
→ excellent resonators







band edge resonator

lateral feedback with low group velocity at flat band edge

defect-cavity resonator

band gap confinement

• when incorporate active materials (QDs or QWs)
→ low threshold and high speed lasers

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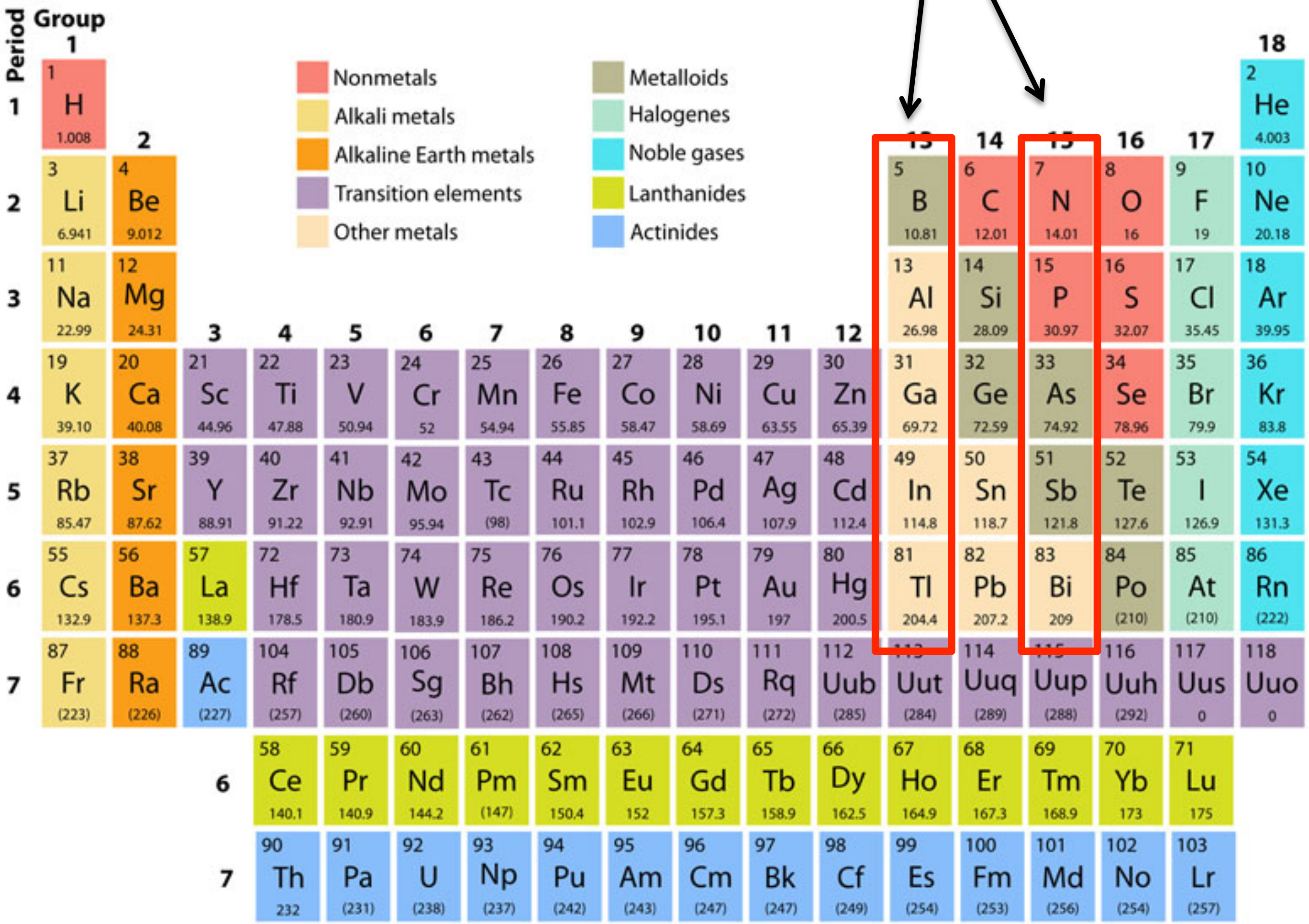
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

PhC laser: How do you go about it?

Active materials: III-V semiconductors



GaN: visible

GaAs:below 1µm

InP: telecom

DIRECT BANDGAP → radiative recombination

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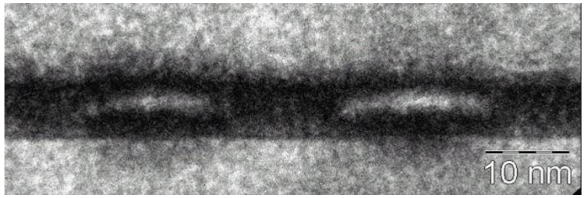
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

PhC laser: How do you go about it?

Active materials: III-V semiconductors

Quantum Dots



Artificial atoms – 3D confinement

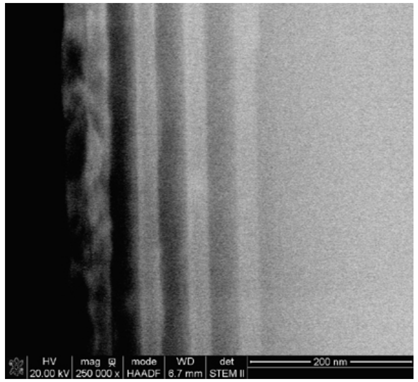
→ 2 levels system

→ gain bandwidth given by inhomogeneous broadening

→ High gain but low density

useful for QED

Quantum Wells



1D confinement

→ gain bandwidth given by temperature

→ Higher gain due to better overlap with optical mode

useful for device

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LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Rate equations model

Photon density in the lasing mode

$$\frac{dS}{dt} = \frac{\Gamma\beta}{\tau_{rad}} N - \frac{S}{\tau_p} + \Gamma v_g \sigma \left(N - N_{tr} \right) S$$

Carrier density

$$\frac{dN}{dt} = R - \frac{N}{\tau_{rad}} - \frac{N}{\tau_{Nrad}} - v_g \sigma (N - N_{tr}) S$$

τ_{rad} , τ_{Nrad} carrier lifetimes associated with radiative and non radiative recombinations

Γ confinement factor

β coupling of spontaneous emission into the lasing mode

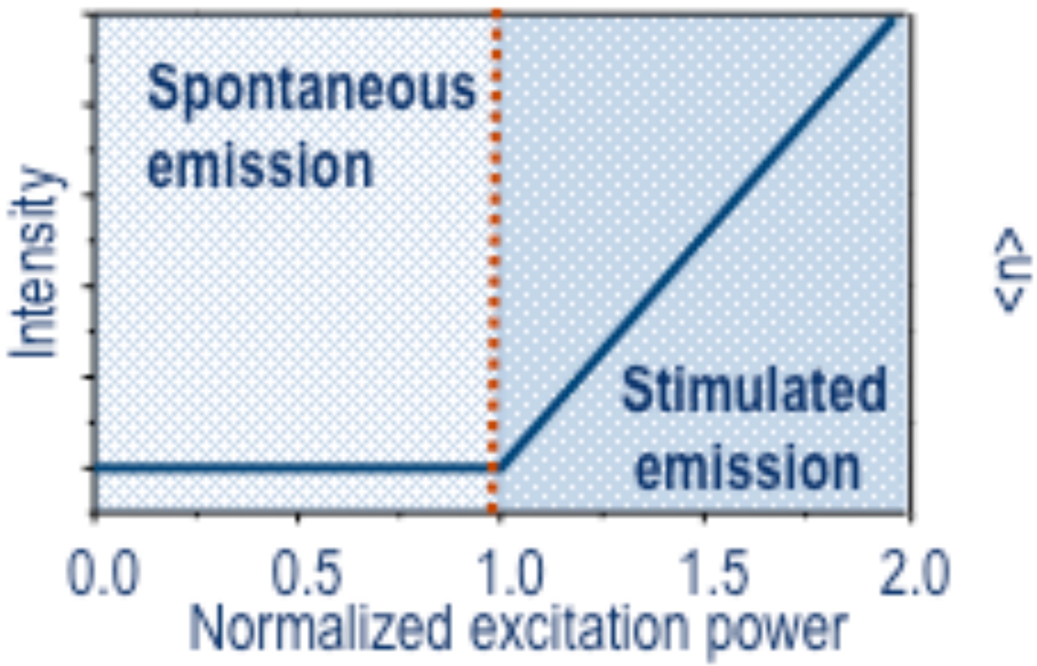
τ_p photon lifetime

v_g group velocity

σ differential gain

N_{tr} carrier density @ transparency

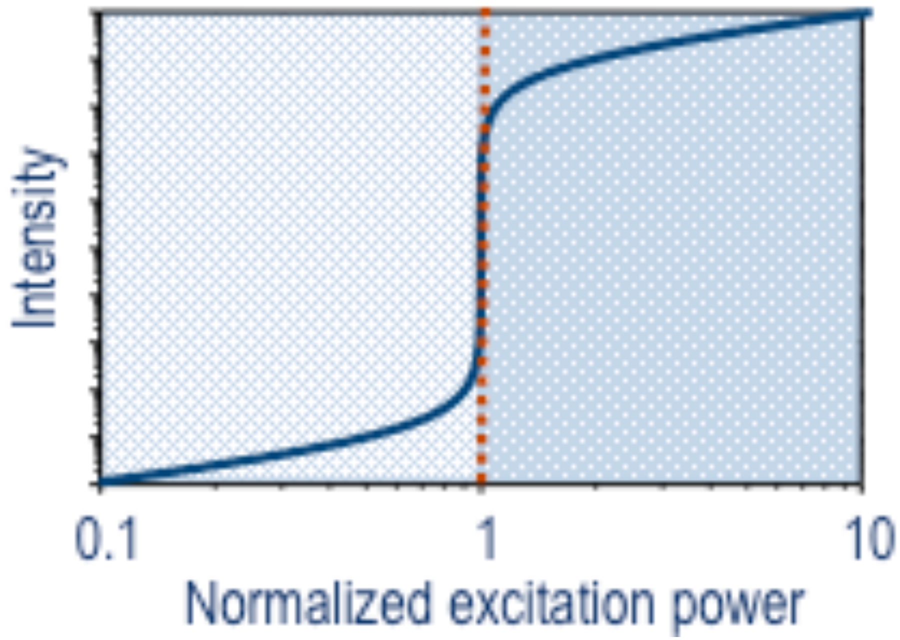
In the stationary regime → Laser characteristics curve



Laser threshold given by gain=losses (classical definition)

In the stationary regime → Laser characteristics curve

Log-Log Scale



Laser threshold given by gain=losses (classical definition)

What is special with PhC nanolasers?

- **High Q and small modal volumes → threshold lowering (fJ!)**

$$I_{th} = \frac{q}{\beta \tau_p}\left(1 + \frac{N_{tr}\beta V \tau_p}{\tau_{rad}}\right)\left(1 + \frac{\tau_{rad}}{\tau_{Nrad}}\right)$$

- **β coupling of spontaneous emission is close to 1!**

→ Spatial redistribution of spontaneous emission into the useful mode due to suppression of other modes (band gap), and Purcell effect

What is special with PhC nanolasers?

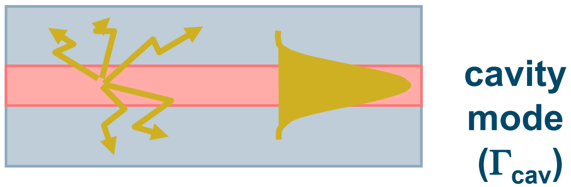
• **β coupling of spontaneous emission is close to 1!**

→ Spatial redistribution of spontaneous emission into the useful mode due to suppression of other modes (band gap), and Purcell effect

Light-matter interaction in semiconductor materials

acceleration of spontaneous emission given by

$$F_p = \frac{\Gamma_{cav}}{\Gamma_{all}} = \frac{3}{4\pi^2}\frac{Q}{V/\lambda^3}$$



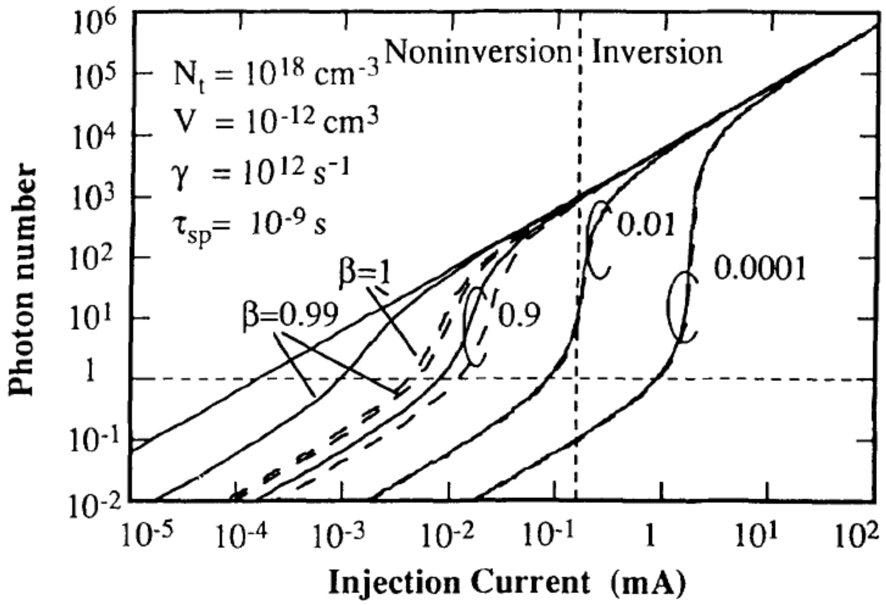
Q=Max(Q_{cav},$Q_{emitter}$)

$$\beta = \frac{F_p}{\gamma + F_p}$$

What is special with PhC nanolasers?

- **β coupling of spontaneous emission is close to 1!**

→ Threshold-less lasers?



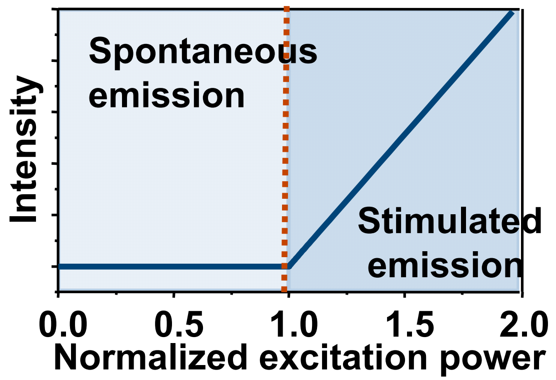
From G. Bjork et al, Phys. Rev. A, 50 1675-80 (1994)

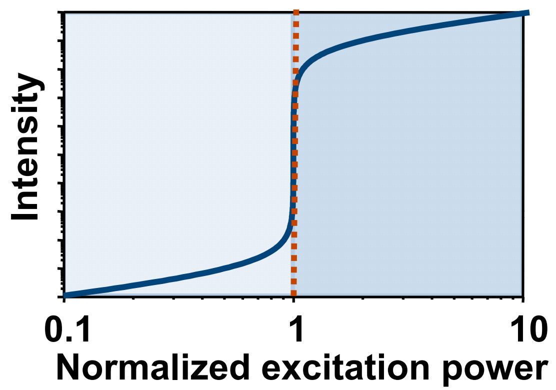
No! New definitions of threshold!

Identifying the laser threshold

Classical definition

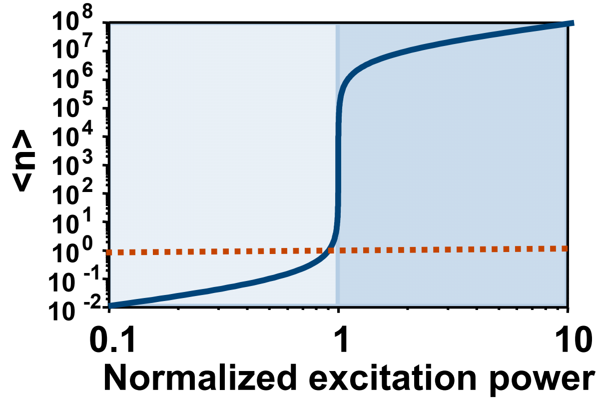
Gain = losses





Quantum definition

Photon number in the usefull mode <n>=1

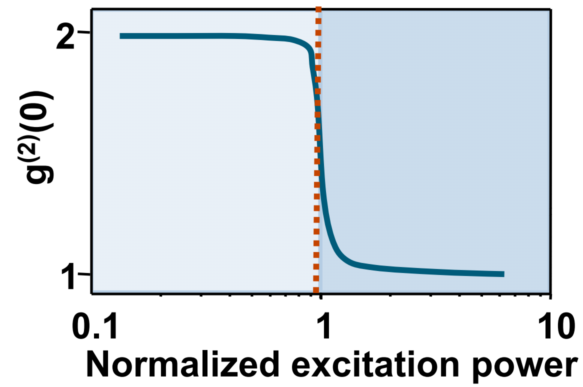


For some high-β lasers, these two definitions do not coïncide.

N.J. Van Druten *et al*, Phys. Rev. A 62, 05308 (2000)

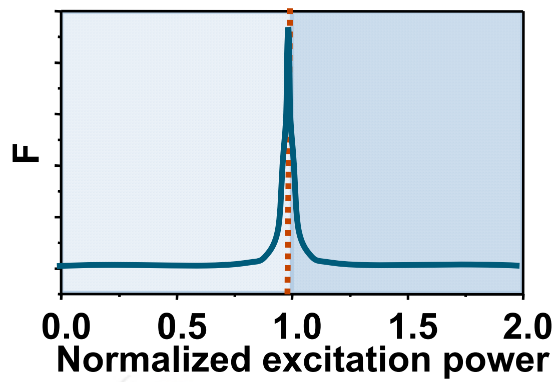
Statistical definition

Second-order coherence $g^{(2)}(0)$



Fano factor

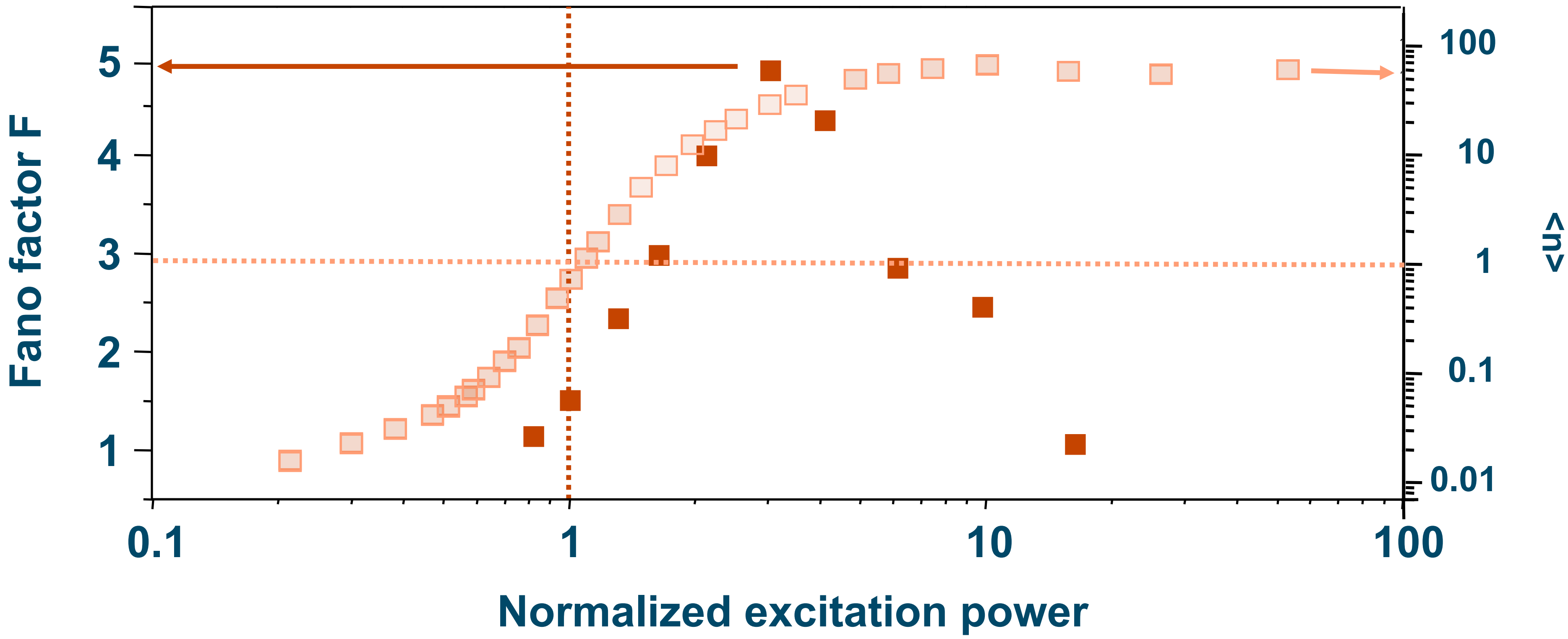
$F = \langle n\rangle(g^{(2)}(0)-1)+1$



Experimental observation in 2D PhC cavity + QDs

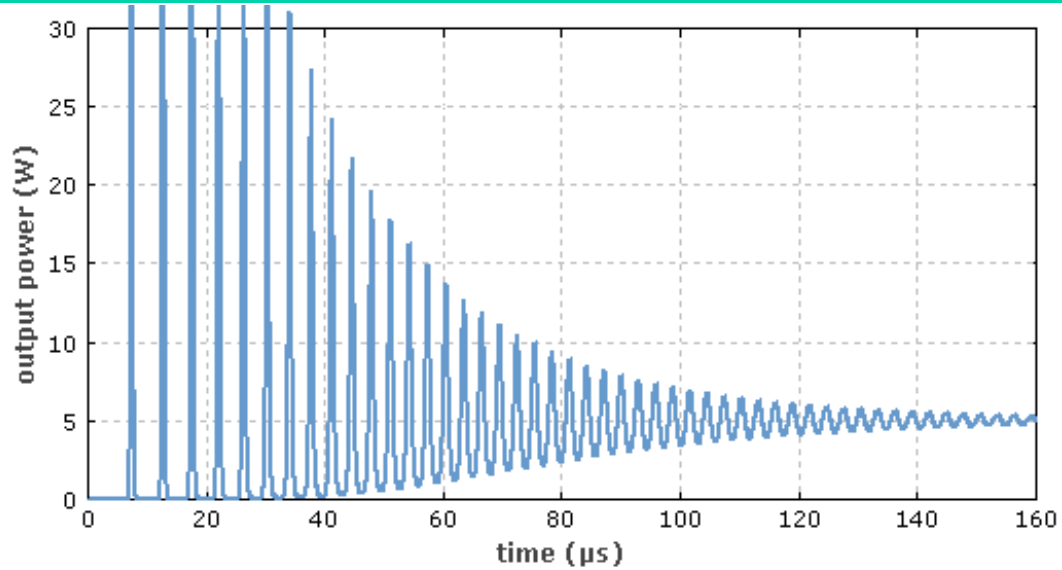
- **Measurements@lpn**
  - Fano factor as a function of excitation power

F = <n>($g^{(2)}$(0)-1)+1



Semiconductor lasers are class B lasers! (carrier lifetime > photon lifetime)

→ **abrupt change in pump gives relaxation oscillations**



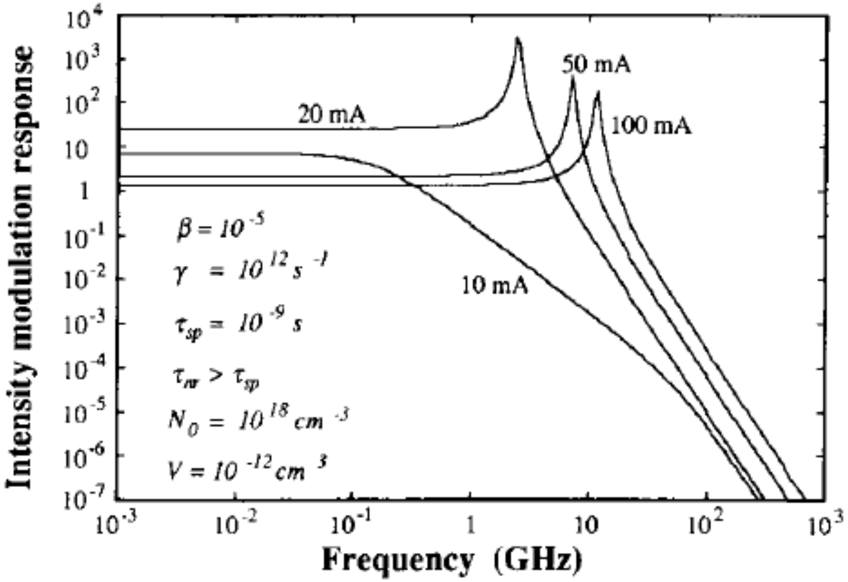
Frequency and damping time depend strongly on β

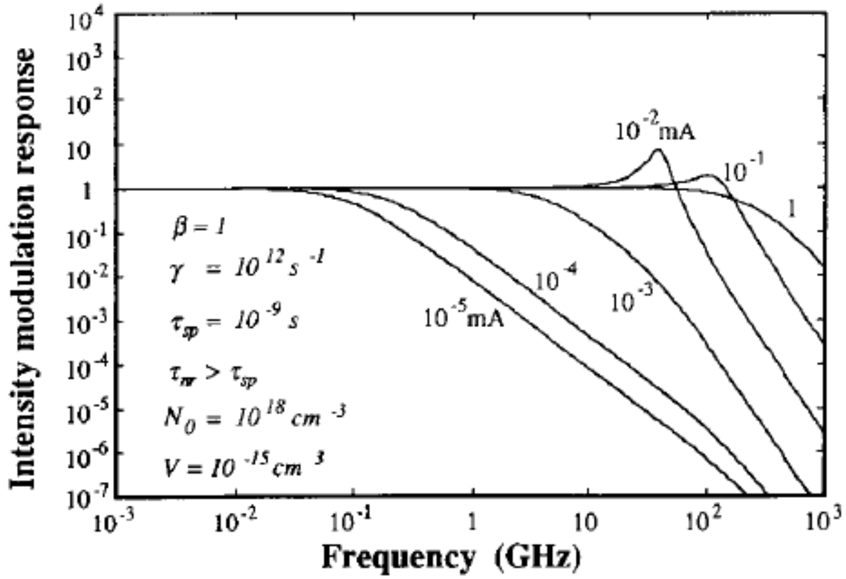
→ **response to a short pulse pump depends on photon lifetime, carrier lifetime and on β**

What is special with PhC nanolasers?

• β coupling of spontaneous emission is close to 1!

→ **Very fast dynamics!**

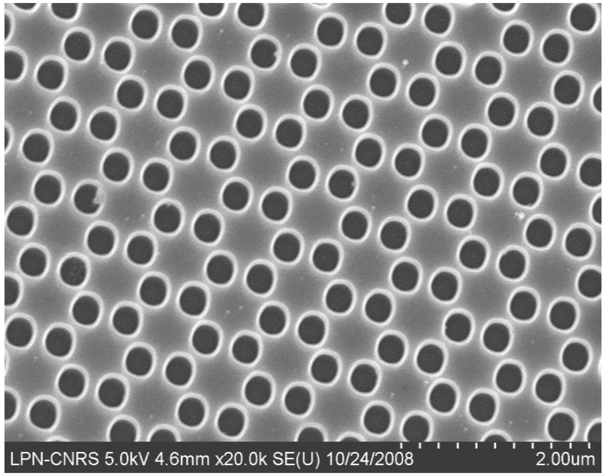




from G. Bjork et al, JQE 27, 2386-96 (1991)

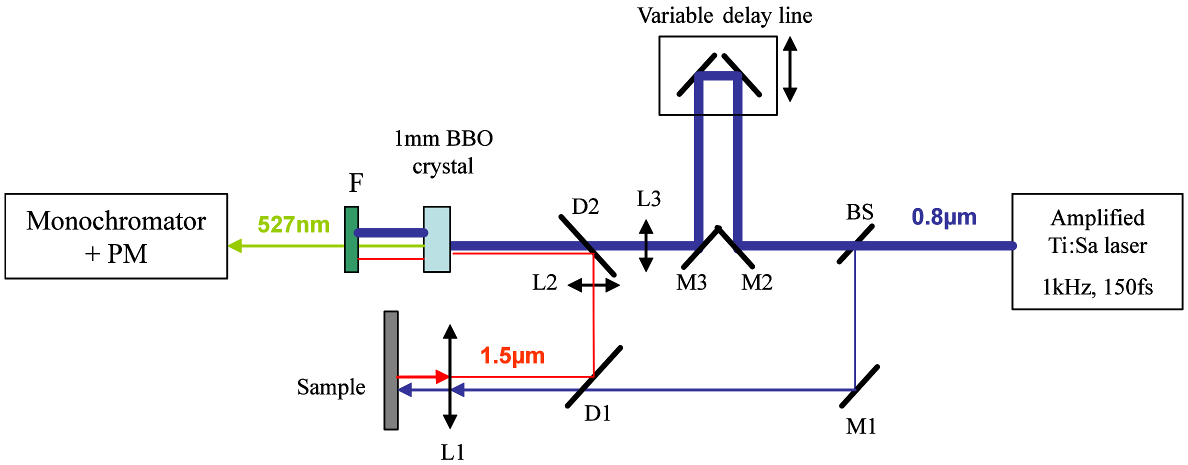
→ **100GHz modulation possible!**

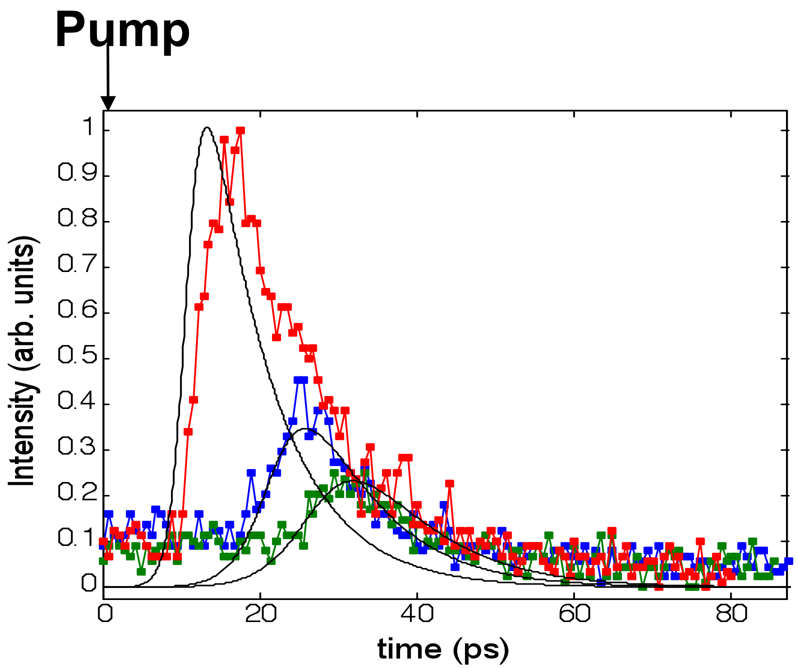
Band edge laser @1.55μm



Some experiments

Up-conversion gating technique





F. Raineri et al, Opt. Express 17, 3165-72 (2009)

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Some experiments on nanocavities

H. Altug, Nat. Phys. 2, 484-88 (2006)

950nm Nanocavity laser

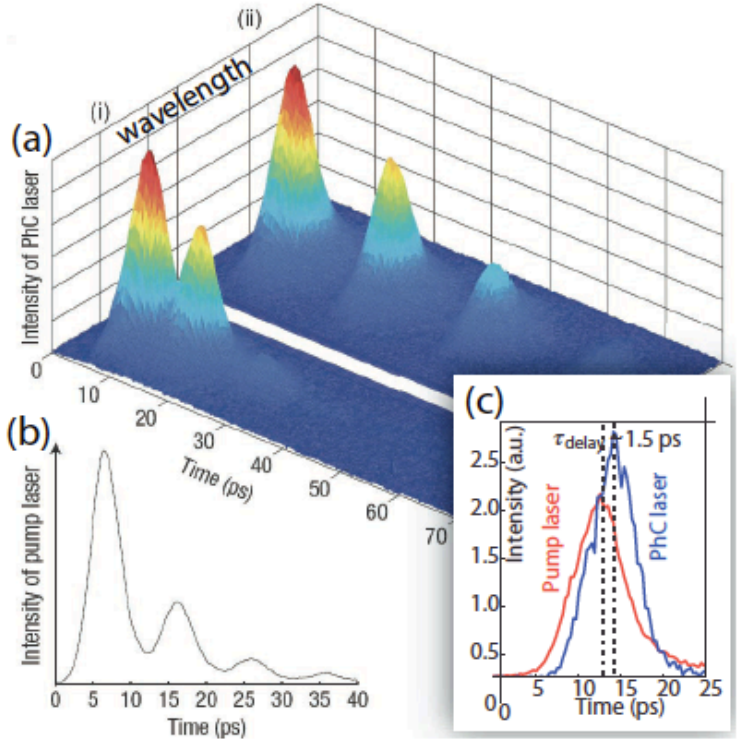

Figure 8 (online color at: www.lpr-journal.org) Large-signal lasing response in QW-driven PC laser. (a) Response to excitation pulses at (i) 9 ± 0.5 and (ii) 15 ps. (b) Excitation pulse train created by etalon setup. Imperfect mirror arrangement causes an exponential decrease in pulse power and only the first three pulses exceed the photonic crystal lasing threshold. (c) Lasing response delay.

S. Matsuo et al, Opt. Express 19, 2242-2250 (2011)

1550nm Nanocavity laser

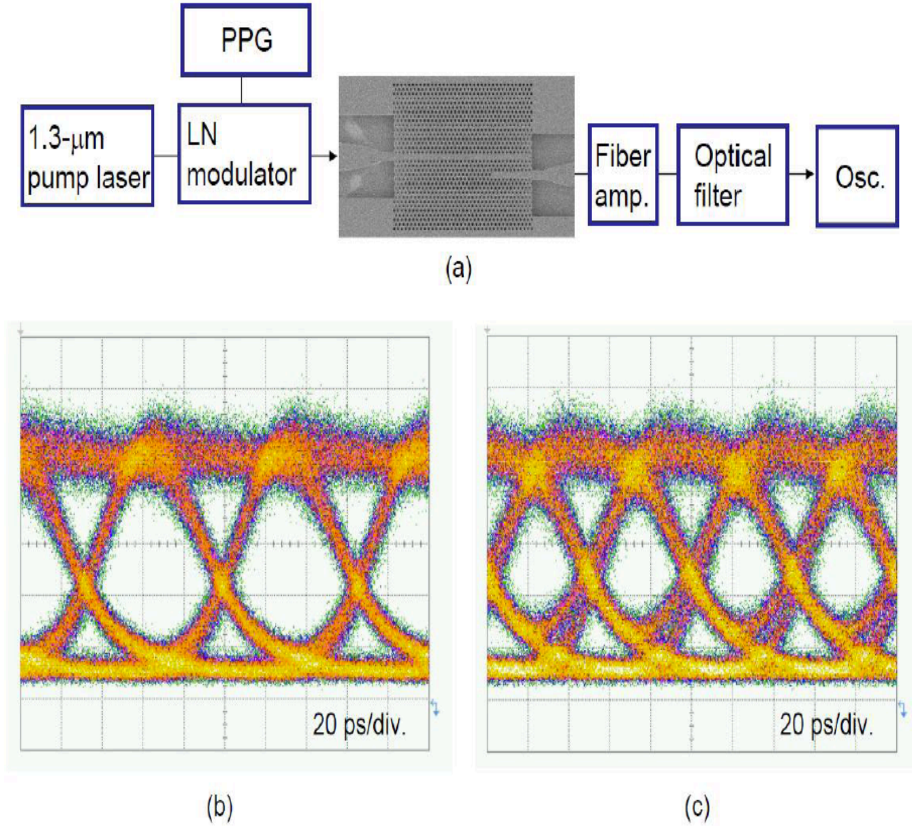

Fig. 6. (a) Experimental setup for direct modulation. Eye diagrams for (b) 15 Gbit/s and (c) 20 Gbit/s NRZ signals.

1- Photonic crystal lasers: ultimate lasers?
→ How do you go about it?
→ Unique properties: static and dynamic properties

2- Ready for application? Some issues
→ Interfacing
→ Electrical injection

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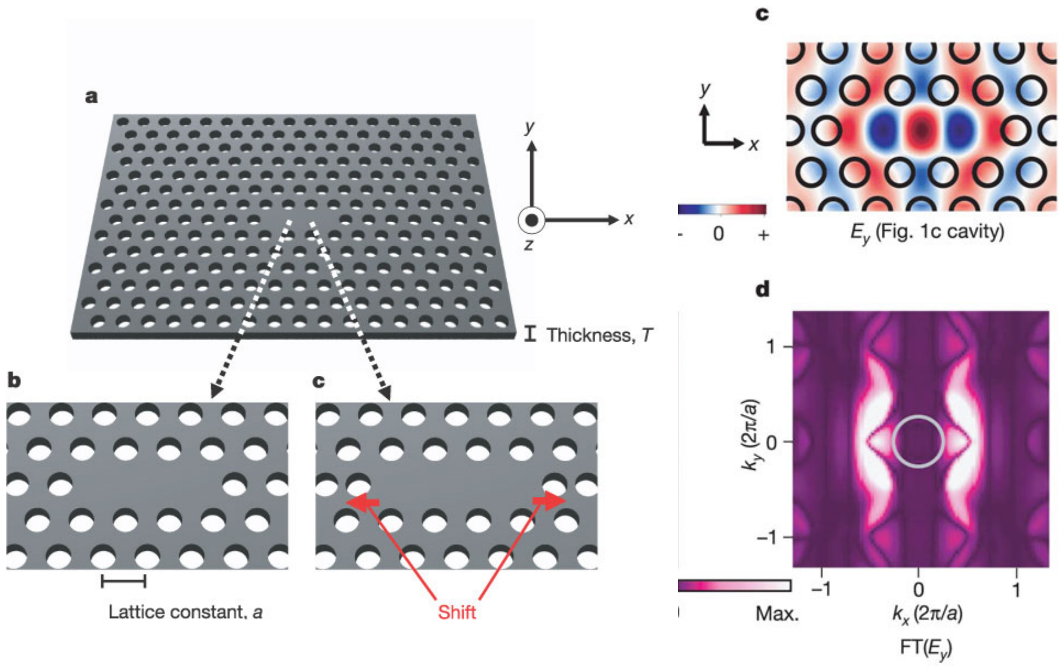
Interfacing PhC lasers with the external world

- 2DPhC lasers are very difficult to communicate with because of the strong confinement of light within cavity



- problem of integration of passive material with active material

What are the solutions?

1- Photonic crystal lasers: ultimate lasers?
→ How do you go about it?
→ Unique properties: static and dynamic properties

2- Ready for application? Some issues
→ Interfacing
→ Electrical injection

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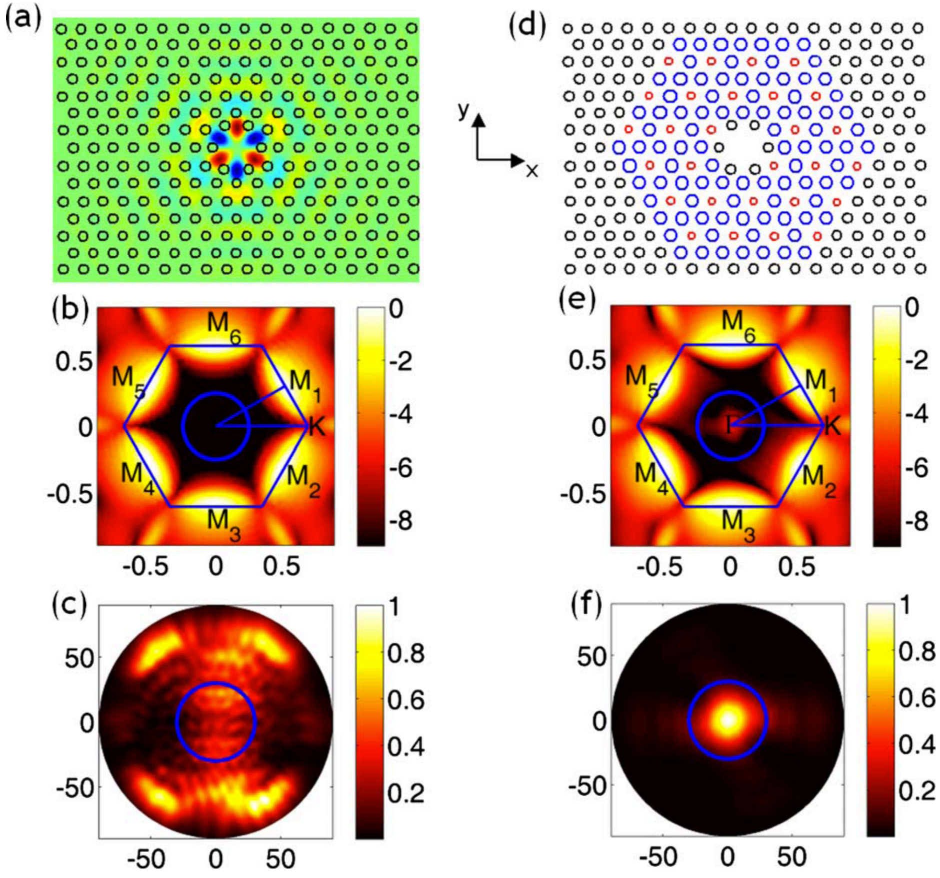
Interfacing PhC lasers with the external world

Engineering of the spatial distribution of the losses: surface emission



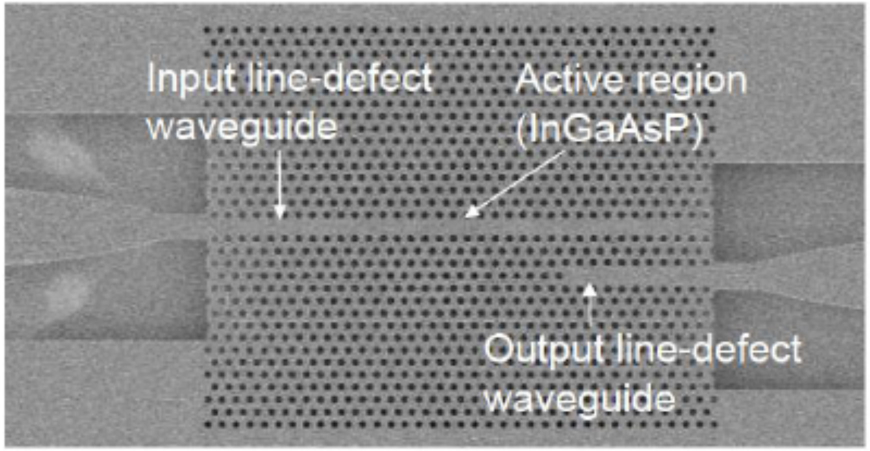
Q.V. Tran et al, Phys. Rev. B 82, 075120 (2010)

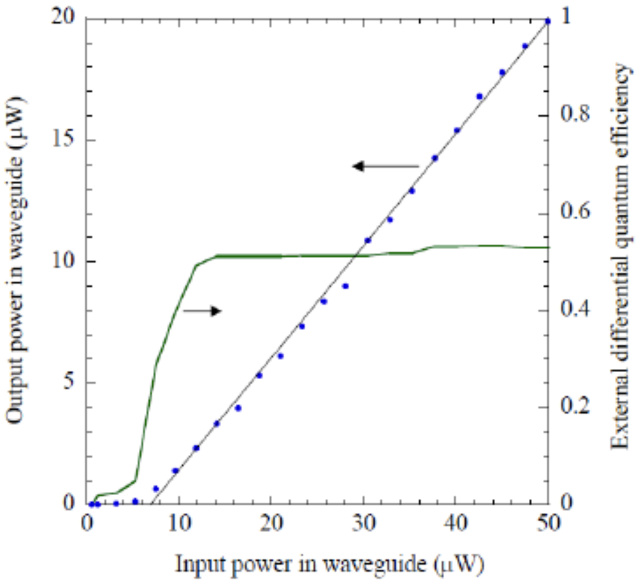
superimposition of a grating

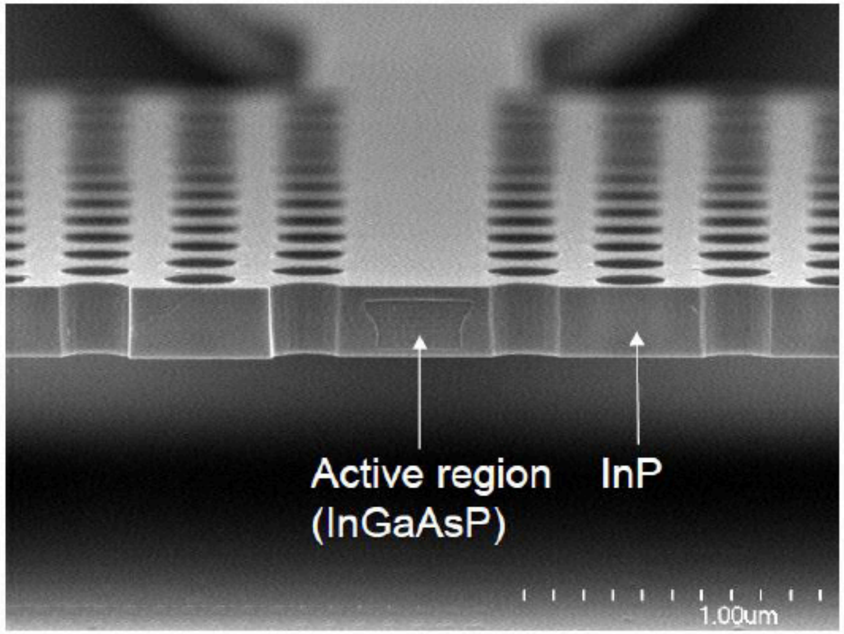
→ **Single device! Is this better than VCSELs?**

Interfacing PhC lasers with the external world

Butt coupling with selective area growth active material (Telecom approach)







S. Matsuo et al, Opt. Express 19, 2242-50 (2011)

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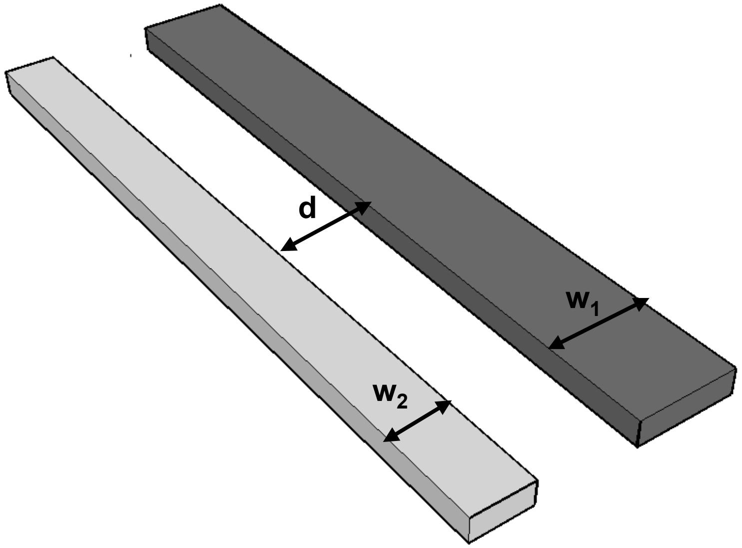
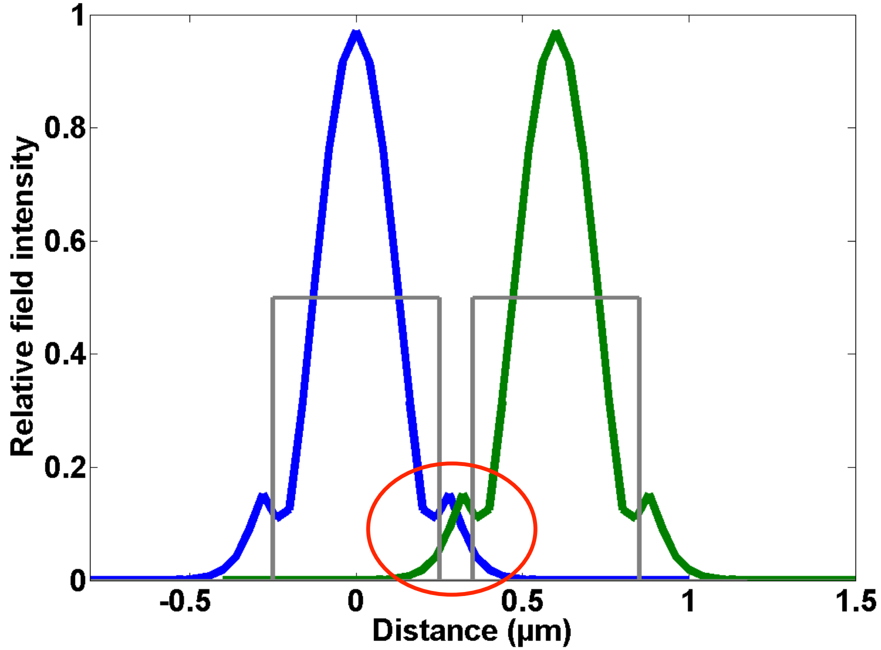
Interfacing PhC lasers with the external world

Evanescent wave coupling

Parallel waveguides:



E_y field amplitude of independent (2D) waveguides (n=3, w=0.5 µm)



Coupling efficiency determined by:

1. **Phase matching** between the original modes
2. **Field overlap** between the original modes

Huang, J. Opt. Soc. Am. A, Vol. 11, No. 3 (1994)

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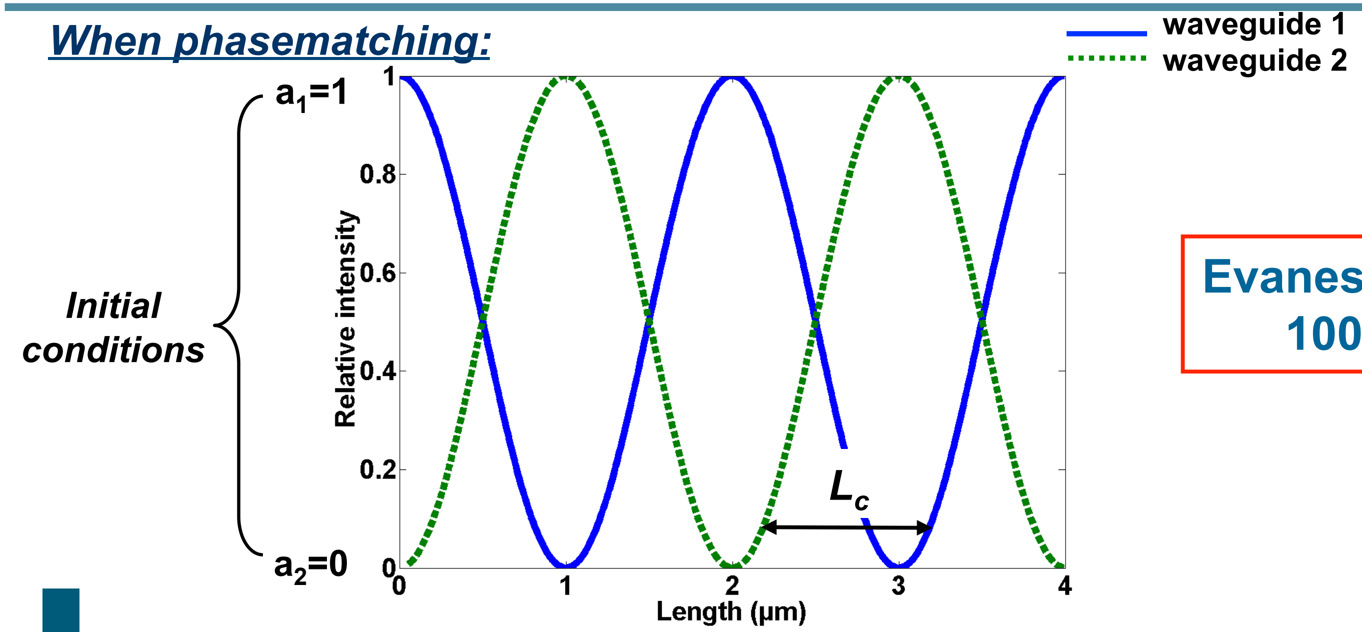
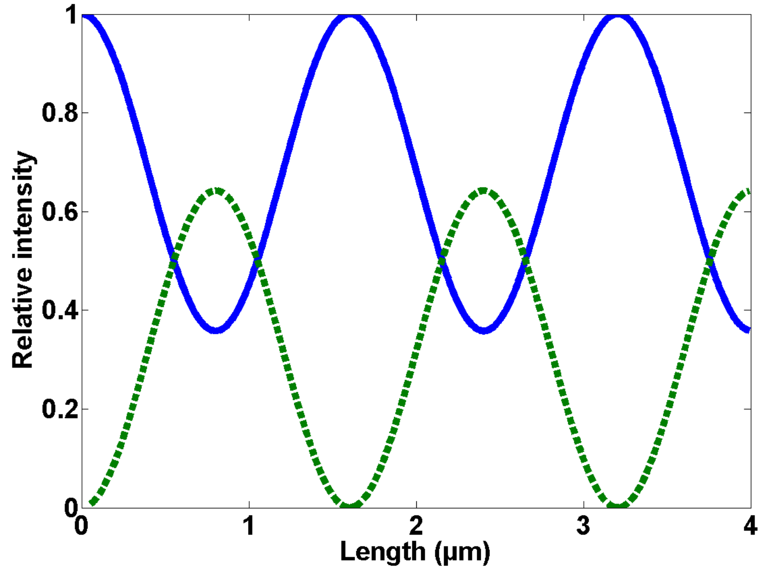
Evanescent coupling: phase matching

When phasematching:



Evanescent coupling can lead to 100% of energy exchange

Maximum energy exchange vs. phase mismatch:

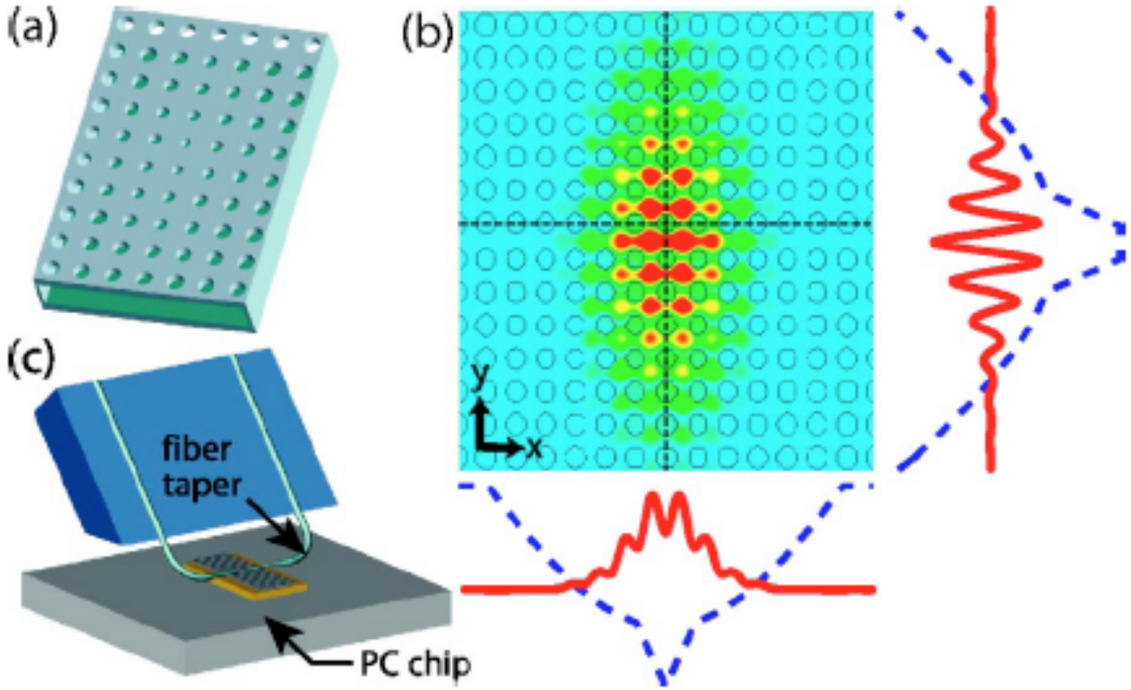


For example :

Δn_{eff} = 10 % implies - 65% of energy exchanged

Interfacing PhC lasers with the external world

Evanescent wave coupling with tapered fibers (for example K. Srivinasan et al, Phys. Rev. B. 70, 081306 (2004)



→ **Single device! low coupling efficiency due to low effective index of the fiber mode!**

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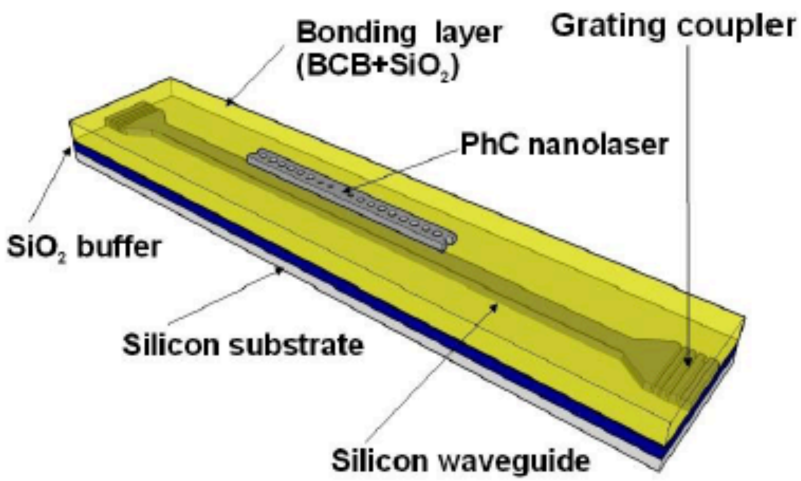
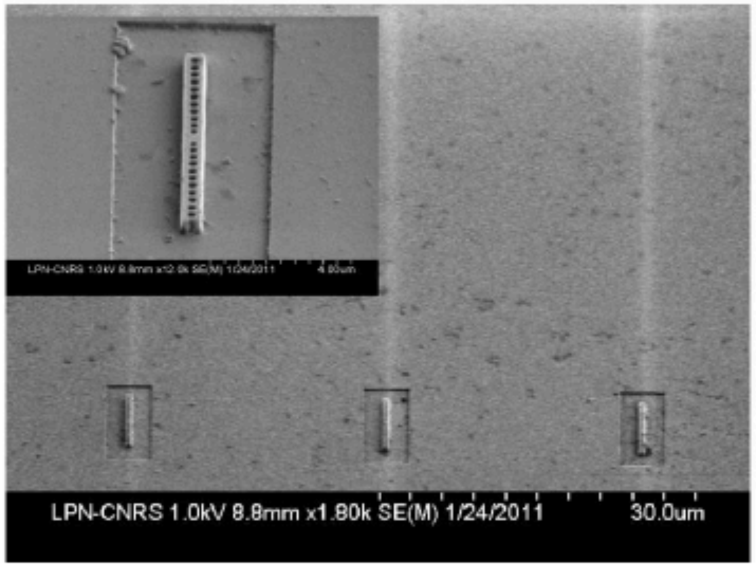
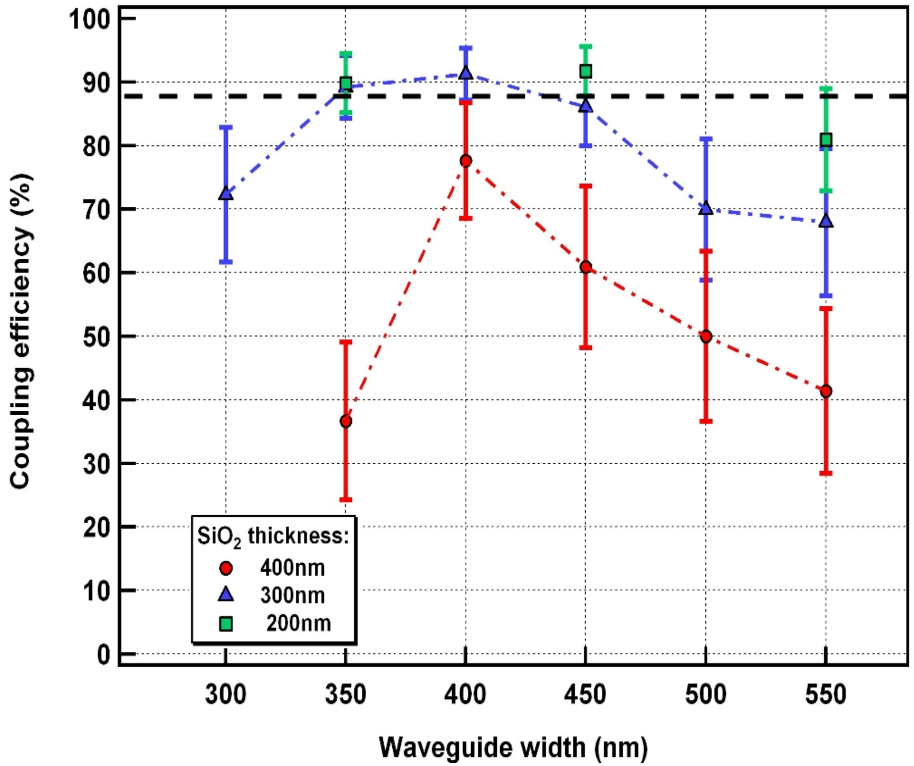
Interfacing PhC lasers with the external world

Evanescent coupling with SOI waveguides circuitry Y. Halioua et al, Opt. Express 19, 9221-31 (2011)







Electrical injection of PhC lasers

• Electrical injection is a major issue. The goal is to inject carriers and make them recombinate within the cavity. The difficulties are:

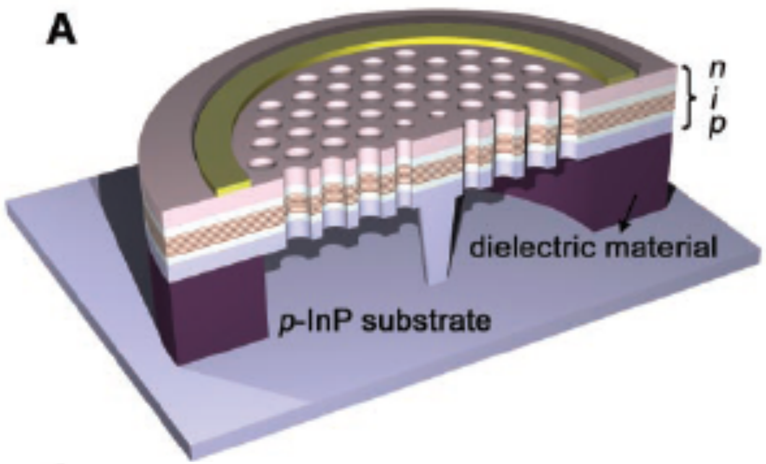
→PhCs are very sensitive to their environment. Contact on top of the cavity isdifficult without destroying the cavity properties

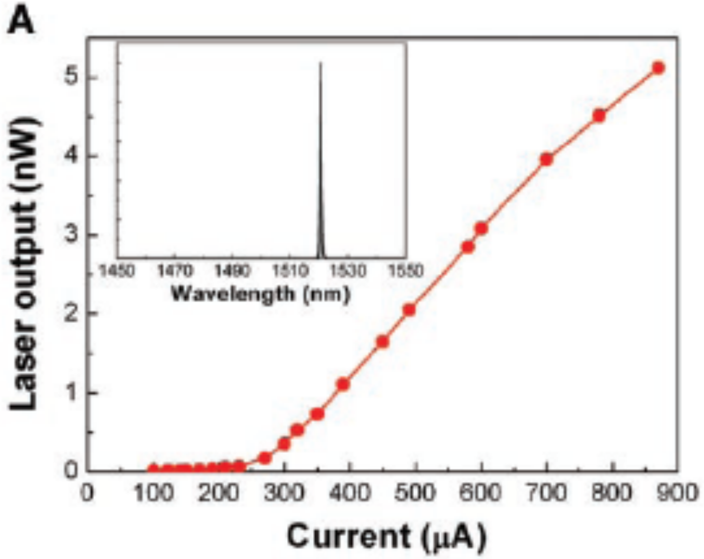
→ the presence of the holes result in an increase electrical resistance (see Anand lecture)

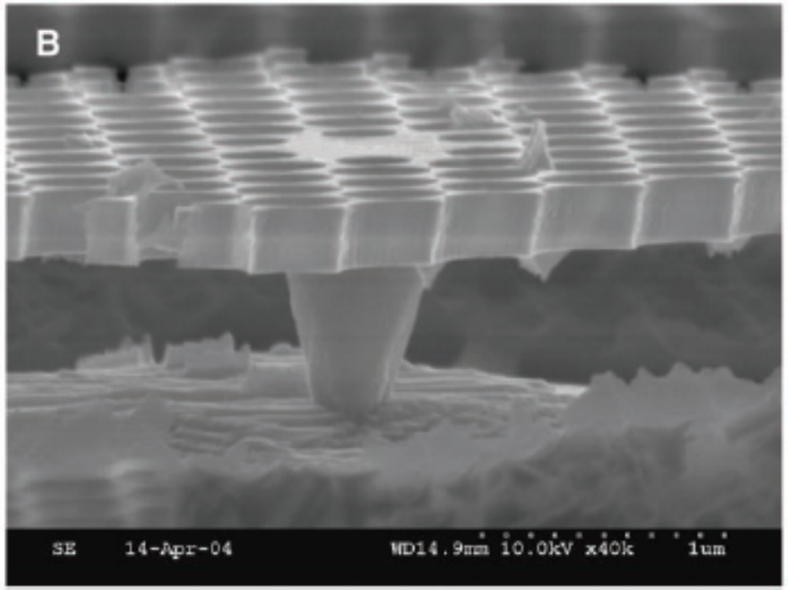
Only 3 groups demonstrated electrical injection of PhC lasers…

Electrical injection of PhC lasers

Smart design of the cavity and acrobatic fabrication…



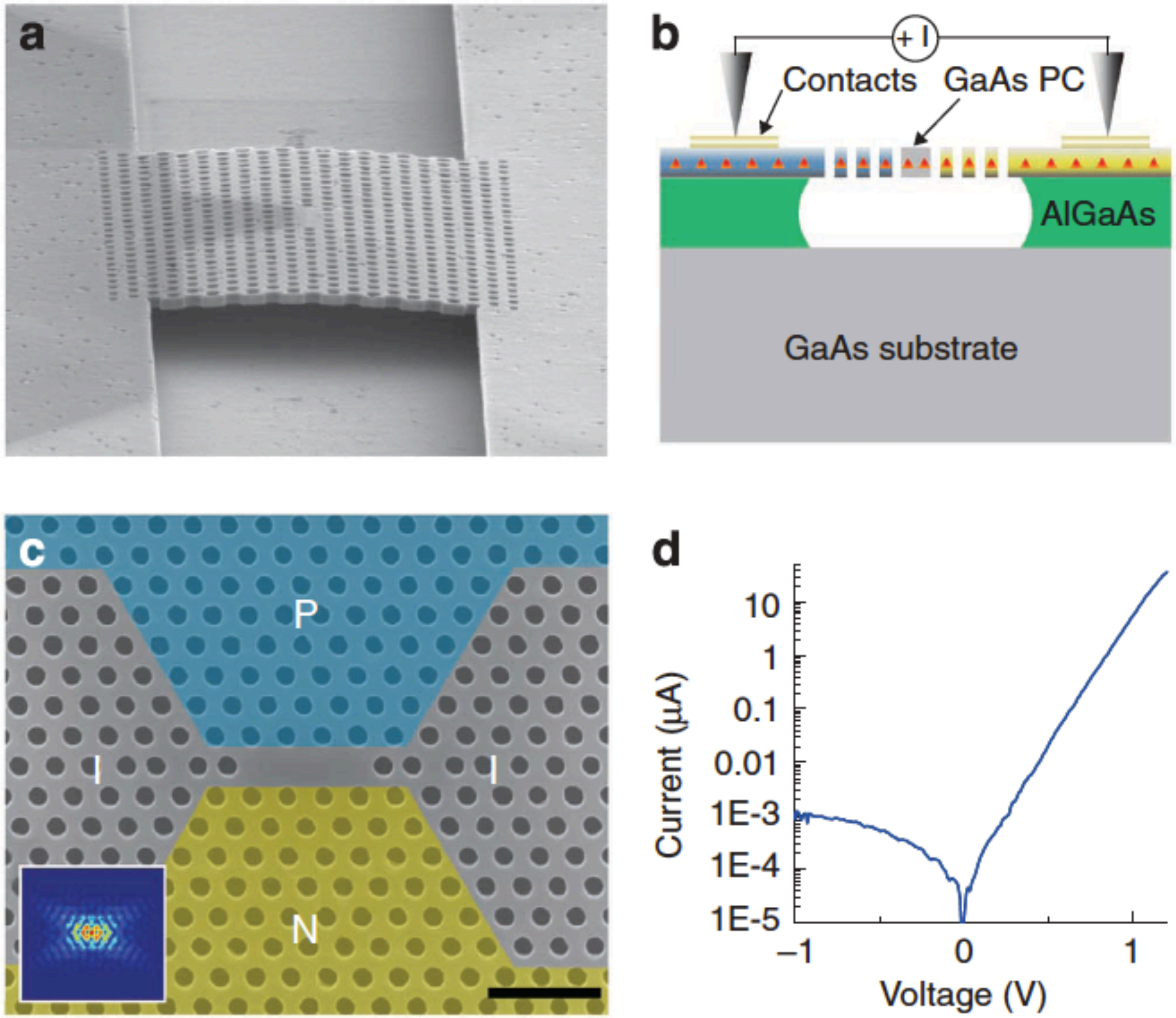


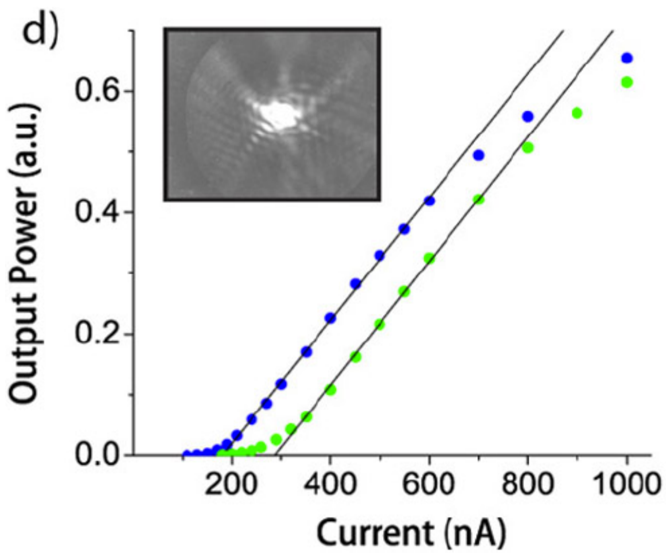


Park et al, Science 305, 1444-47 (2004)

Electrical injection of PhC lasers

Lateral PIN junction in GaAs based system B. Ellis et al, Nat. Photon. 5 , 297-300(2011)





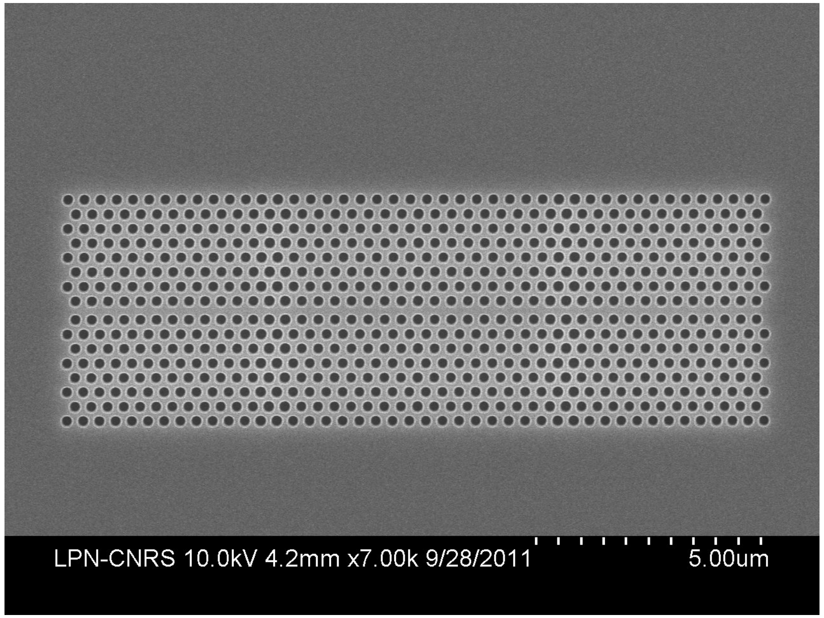
same type of study by NTT on InP (2012

Conclusion

PHOTONIC CRYSTAL PROPERTIES

• By controlling their opto-geometrical features, it is possible to engineer their response
→ slow light waveguides
→ ultimate nanocavity: highest Q/V demonstrated ($Q=10^9$ within $V=(\lambda/n)^3$)

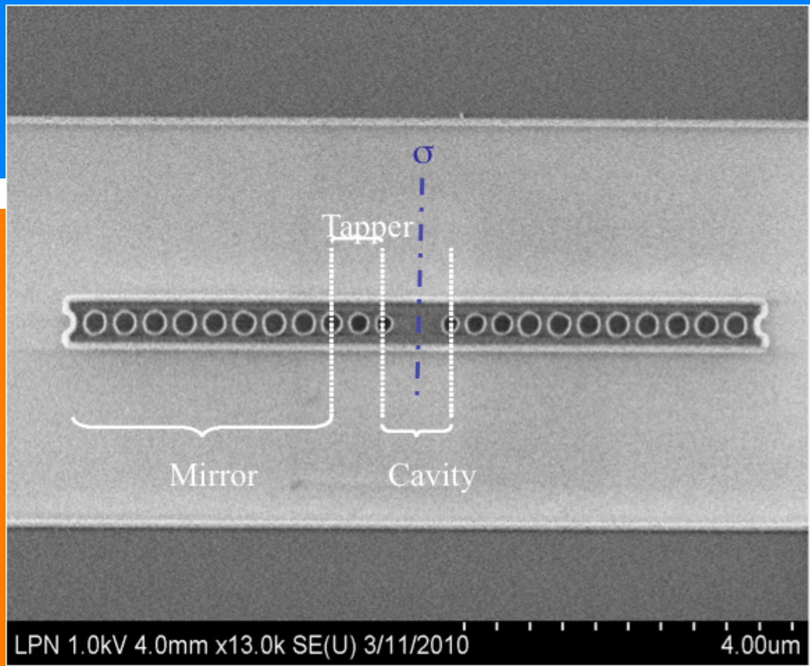
• Ultimate devices in terms of performance such as footprint, activation energy and speed



Conclusion

PHOTONIC CRYSTAL NANOLASERS

- Ultrasmall footprint – smaller than 5μm^2!!
- Threshold of the order of fJ!
- High speed modulation – 100GHz!



SOME ISSUES

- Interfacing
- Electrical pumping
- Heating! (membrane…)
- Weak output power (from nw to 100μW)
- Nano-sensitive → reproducibility of fabrication?
- Sensitive to environment….

→ Still a lot of work to do…

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