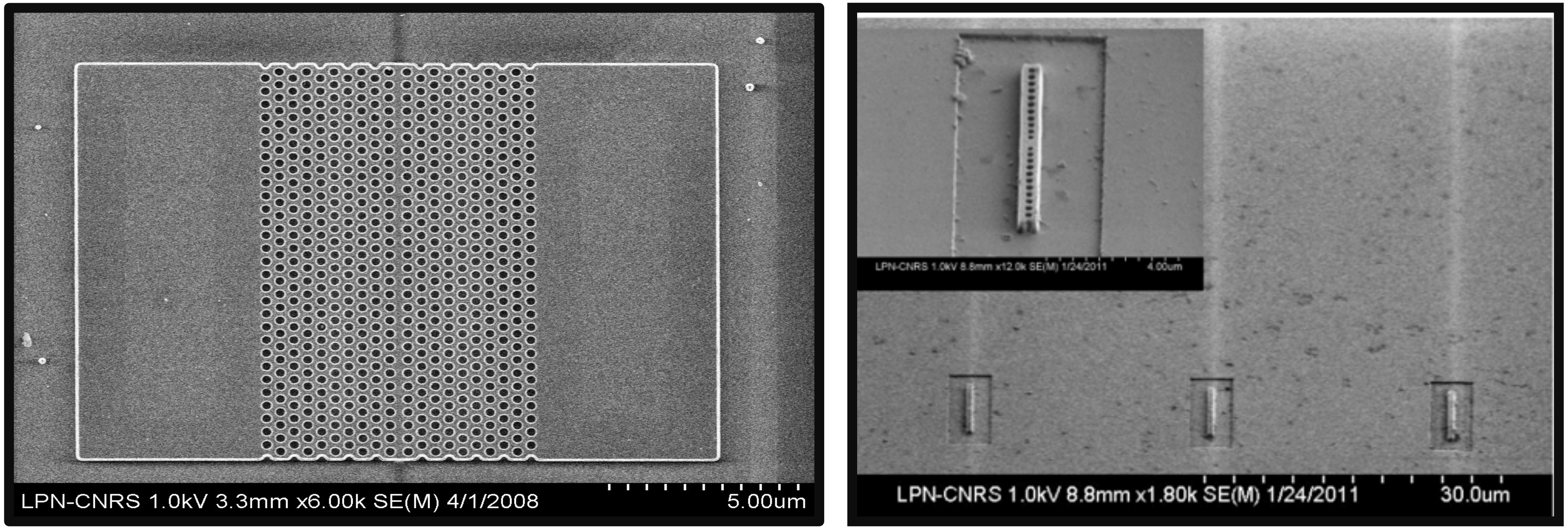
Hybrid III-V/SOI Nanolasers



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[2] Université Paris Diderot – Paris VII

Outline

- Motivations of hybrid photonics and pursued approaches
- III-V/SOI nanophotonics platform
- Nanolasers efficiently coupled to SOI circuitry
- Hybrid memories and switches
- Conclusion and Future Work

Outline

- Motivations of hybrid photonics and state of the art
- III-V/SOI nanophotonics platform
- Nanolasers efficiently coupled to SOI circuitry
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- Conclusion and Future Work

Motivations :

Convergence of µ-electronics & photonics

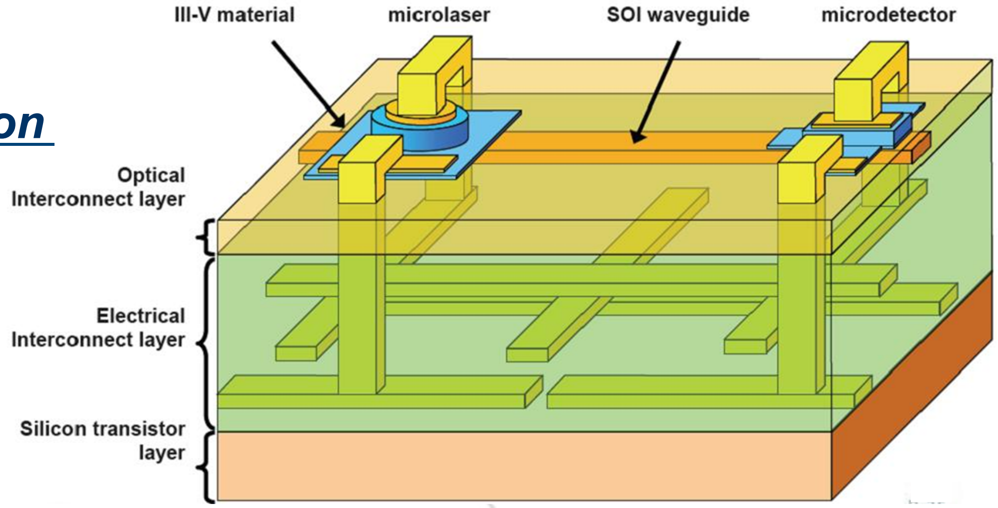
Photonics can help to overcome the limits of electronics, in speed and power consumption, for intra or inter-chip communication
D.A.B. Miller, Proc. IEEE 97, 1166-1185 (2009)

CHALLENGES

- Deliver the necessary passive and active functionalities: low-loss waveguides, filters, sources, switches, detectors…
- Perform low power consumption and high speed: fJ activation energies, >10Gbits/s
- Small footprint for high density (10^4-10^5 of devices per mm^2): $<100\mu m^2$
- Integration with Si electronics and CMOS compatibility for cheap manufacturing

Possible scheme for photonic integration

Ghent Univ.



→ How to go about this?

Motivations :

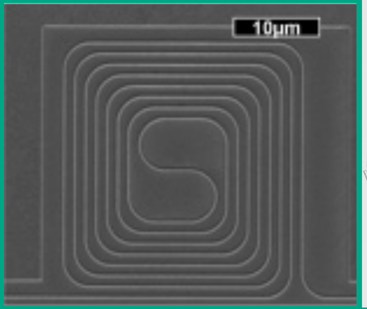
III-V semiconductors/Silicon hybrid structures

Combine the best of both materials for photonics

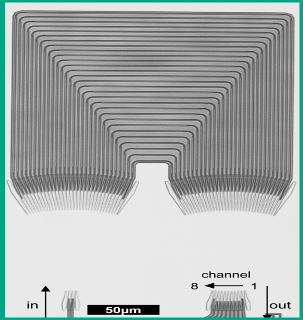
SILICON

- **Compatibility with µ-electronics**
- **Low cost production in CMOS fabs**
- **Ultracompact low loss optical circuitry using SOI**

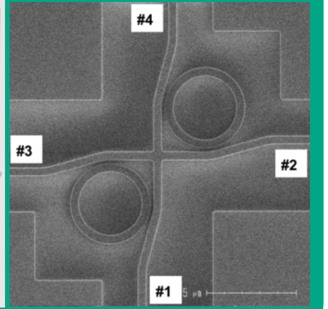
Curved wires



WDM



Add-drop filters



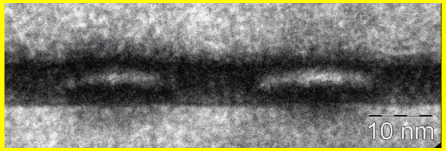
IMEC / INTEC

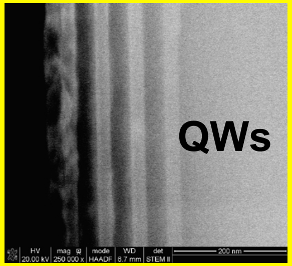
Ideal for passive devices

III-V SEMICONDUCTORS

- **Tailored emission from UV to far IR**
- **High quantum efficiency**
- **Material engineering for high nonlinearity**

QDs





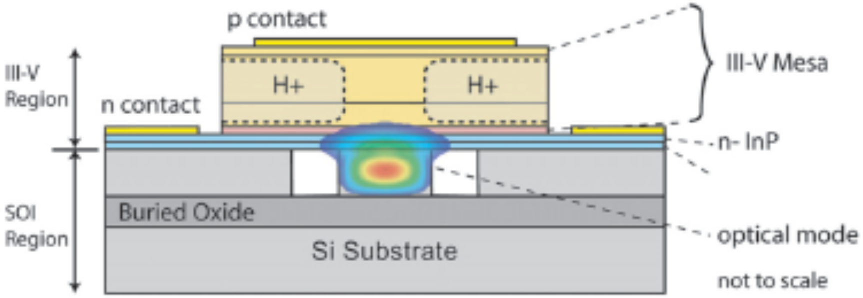
QWs

Ideal for active devices

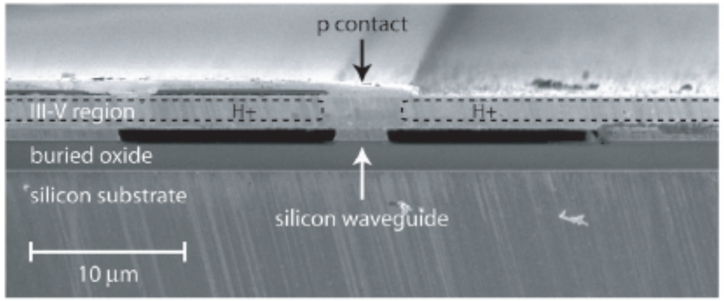
Pursued approaches for heterogeneous integration

III-V and Si in contact → hybrid mode

UCSB/Intel



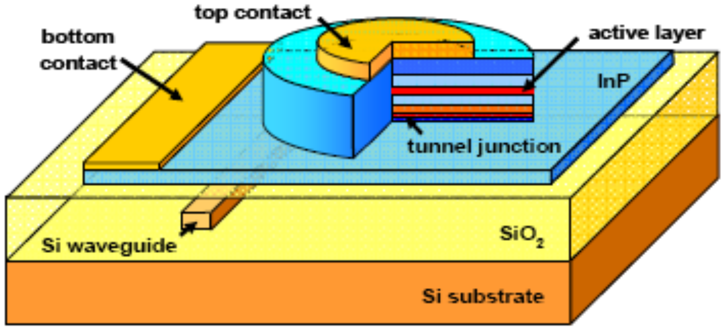
A. W. Fang et al, Materials today 10 (2007)



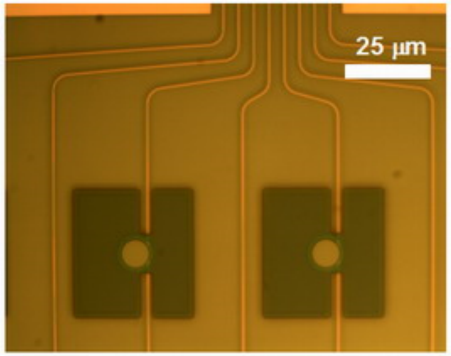
Edge-emitters, DFBs, SOAs, Racetrack lasers, detectors, modulators….

III-V and Si separated by a low index layer → evanescent coupling

IMEC/LETI/INL



J.V. Campenhout et al, Opt. Express 15, 6744 (2007)



µdisks lasers, wavelength converters, memories, detectors…

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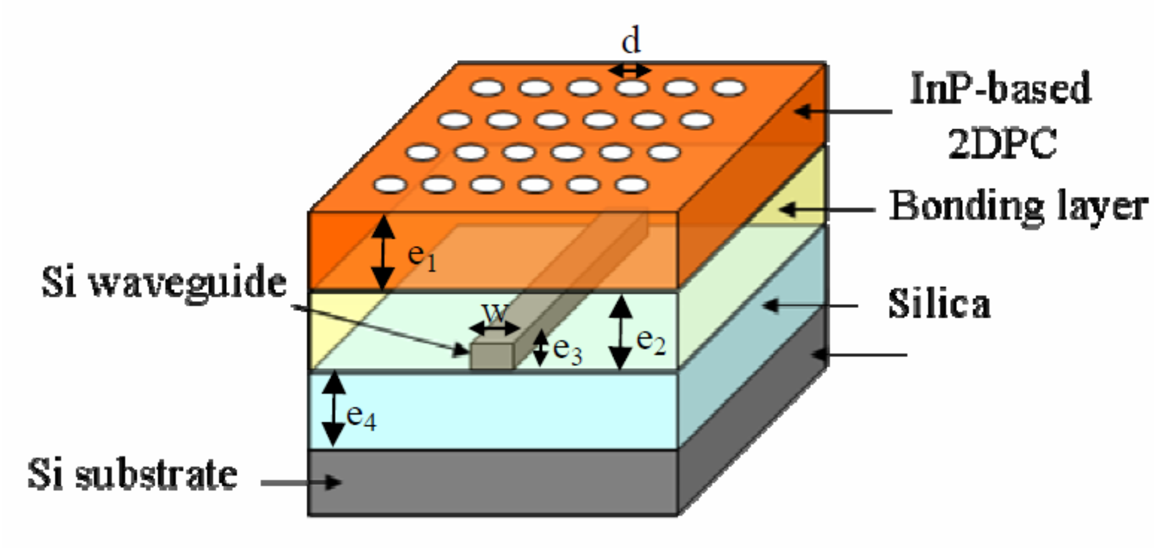
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

LET’S GO FOR “NANO”!



d~250nm
e_1~250nm
e_2~300nm
e_3~200nm
e_4~2µm
w~500nm

→Smaller footprint
→Better power efficiency
→Higher speed

dépasser les frontières

LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Outline

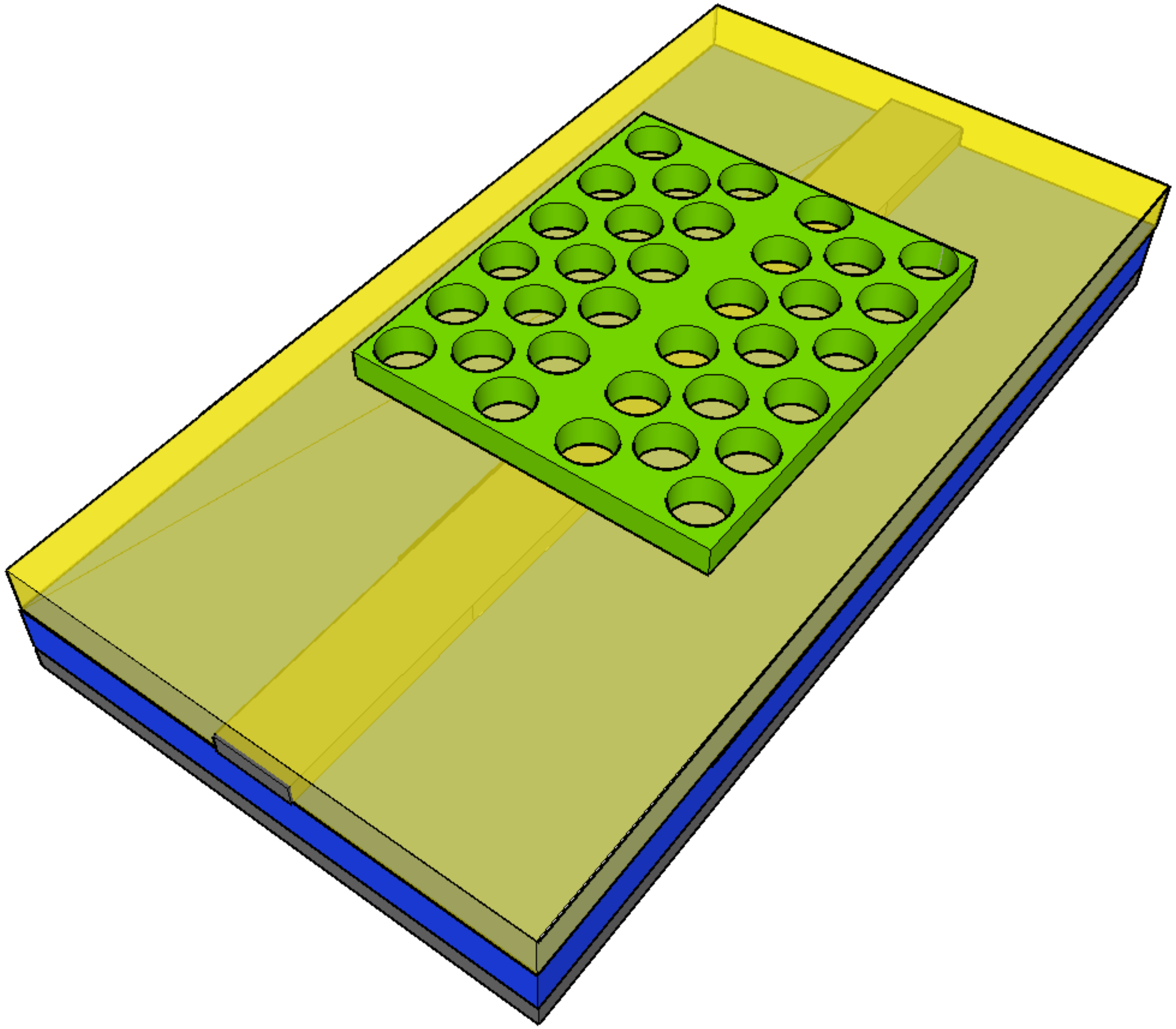
- **Motivations of hybrid photonics and state of the art**
- **III-V/SOI nanophotonics platform**

→ General view

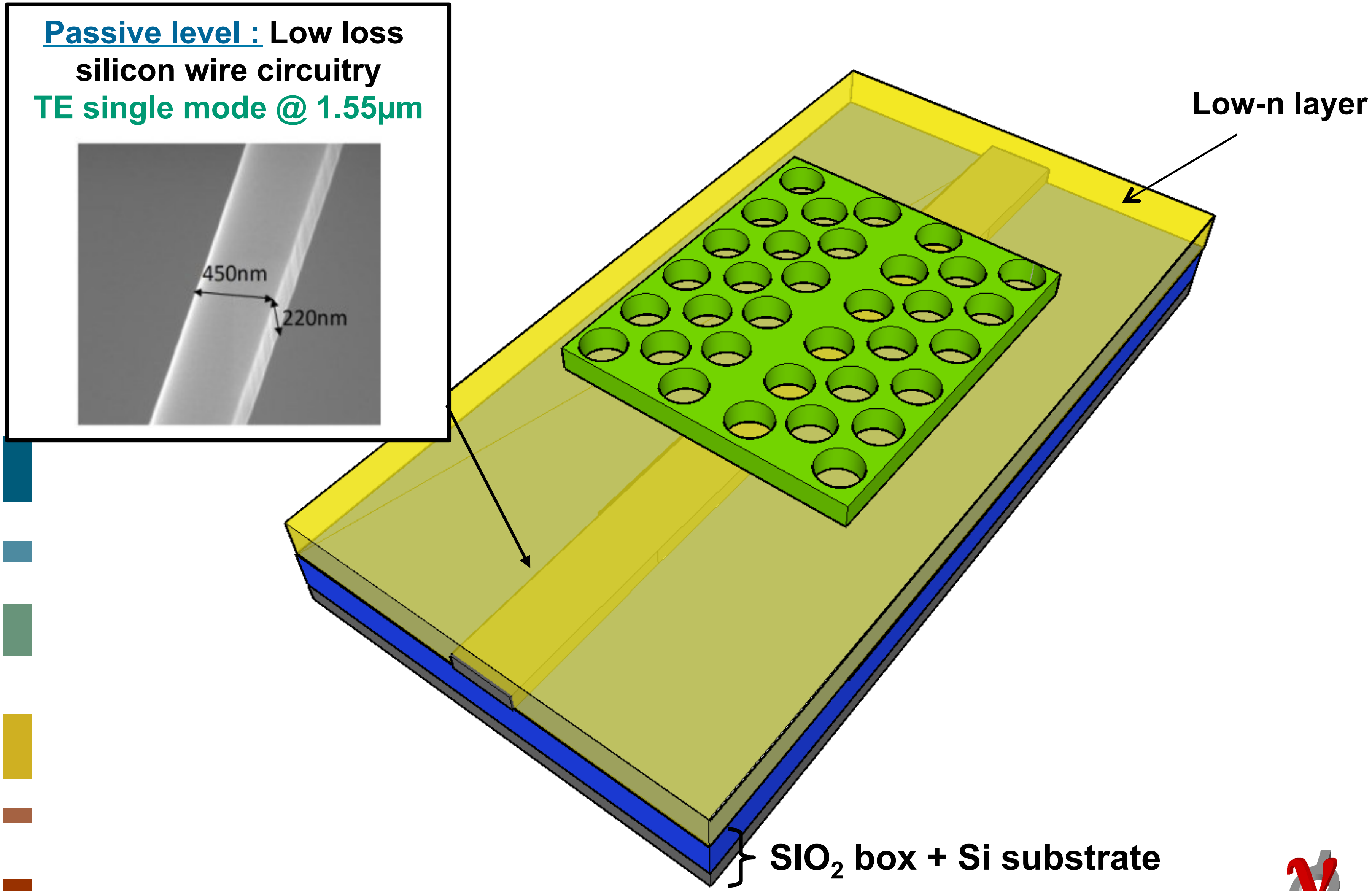
→ PhC lasers properties

- **Nanolasers efficiently coupled to SOI circuitry**
- **Hybrid memories and switches**

General view of the hybrid structure



General view of the hybrid structure: passive level



Passive level : **Low loss silicon wire circuitry**

TE single mode @ 1.55µm

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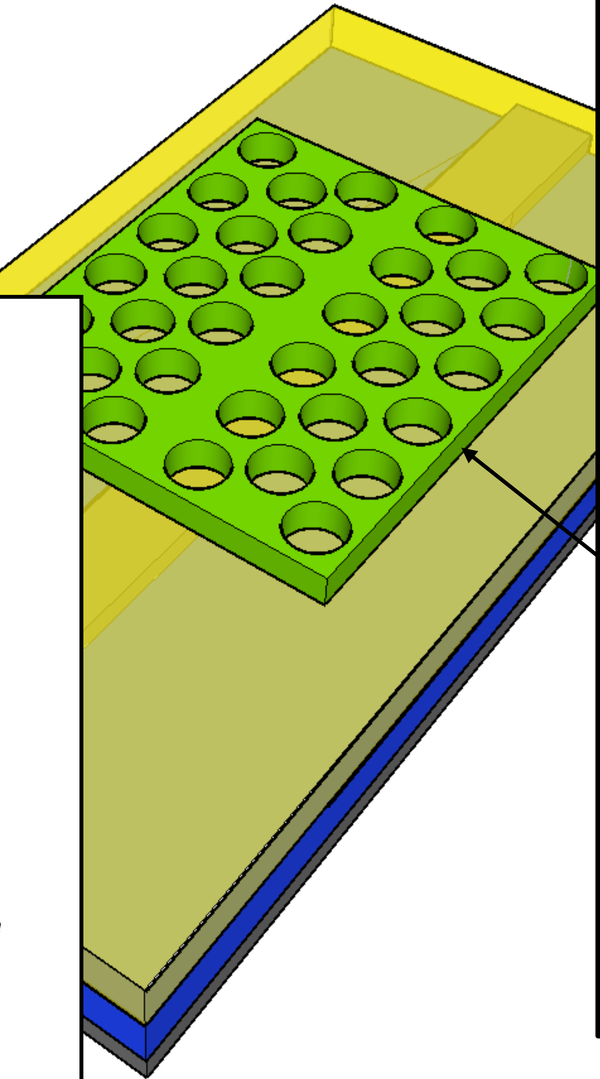
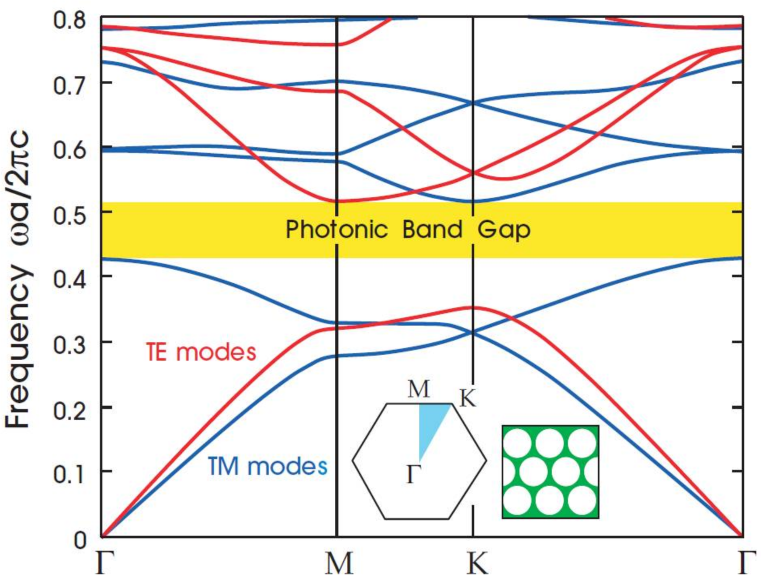
General view of the hybrid structure: active level



Band structure of a 2D PhC:



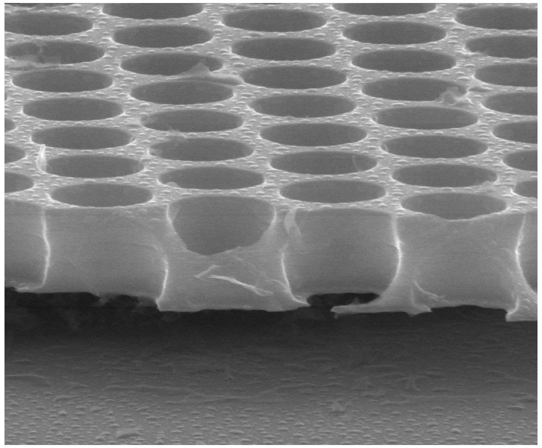
From John D. Joannopoulos – Molding the flow of light

→ Ultimate control of light propagation and confinement

Active level : III-V PhC membrane (InP-based for telecom λ)

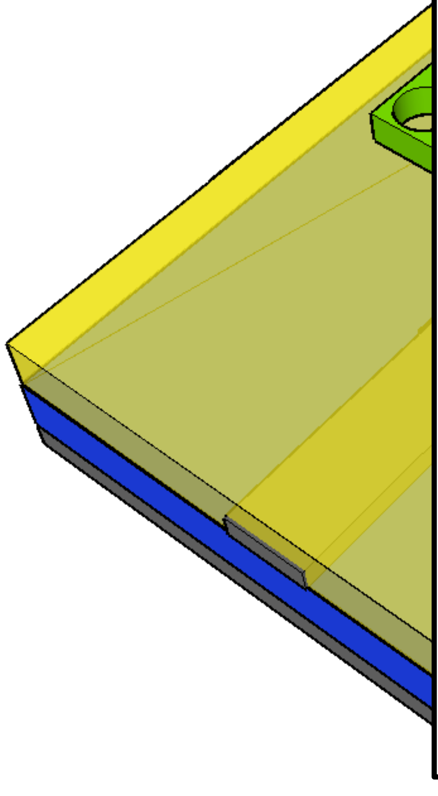
-Periodic structures at λ-scale

S. John, Phys. Rev. Lett. 58, 2486–9 (1987)
E. Yablonovitch, Phys. Rev. Lett., 58, 2059–62 (1987)

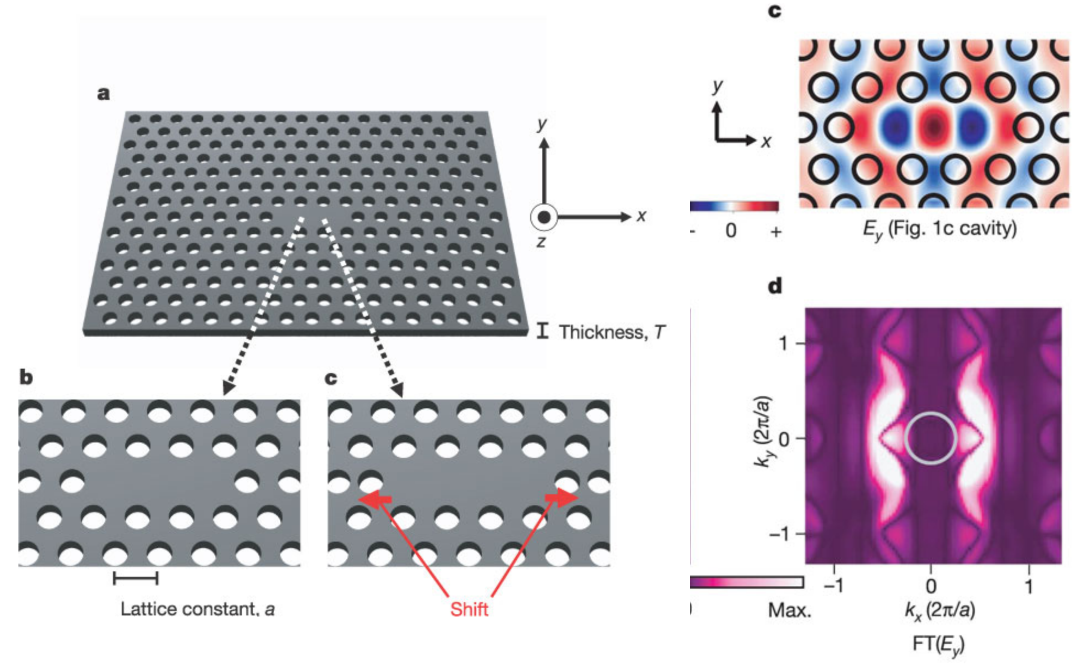


→In plane propagation ruled by periodic patterning
→Vertical confinement thanks to TIR

PhC cavities



Active level : III-V PhCs cavities



Y. Akahane, Nature 425, 944-947(30 October 2003)

High Q ~$10^{4\text{-}8}$, Small modal volume ~$(\lambda/2n)^3$

→ Small footprint (few μm^2)
→ High versatility
→ Nonlinear effects enhancement as *Q/V* or Q^2/V (low activation power)

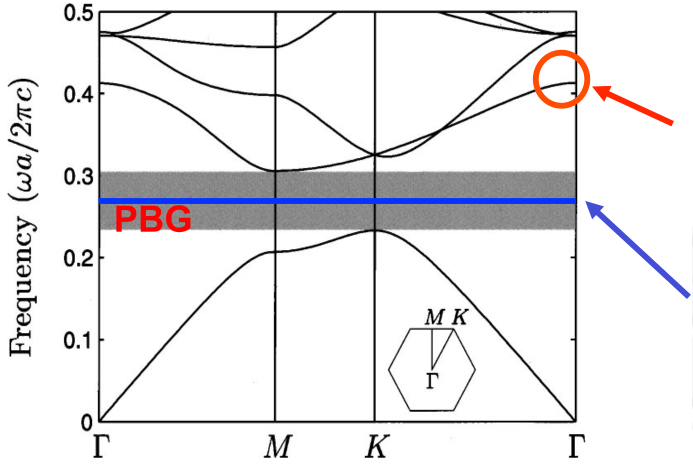
PHOTONIC CRYSTAL LASERS PROPERTIES

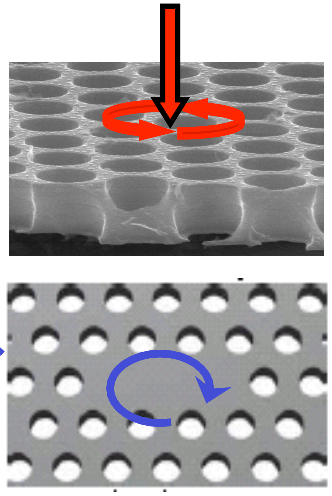
PhC lasers

when we incorporate active materials (QDs or QWs)
→ laser emission

2 types of PhC lasers

triangular 2D PhC for TE-like modes





band/mode edge resonator

lateral feedback with low group velocity at flat band edge

J. Mouette et al, Electron. Lett. 39, 526 (2003)

defect-cavity resonator

band gap confinement

O. Painter et al, Science 284, 1819-1821 (1999)

What is so special?

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**

PhC lasers: Static properties

What is so special with PhC nanolasers?

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

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

M. Notomi et al, Nat. Phot. 4, 648-654 (2010)

- **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

PhC lasers: Static properties

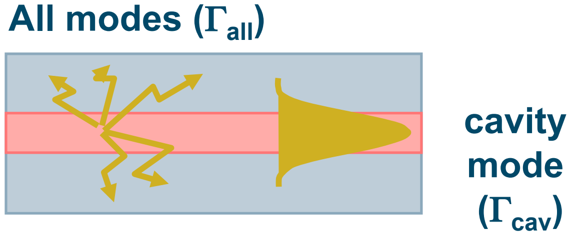
What is so special with PhC nanolasers?

- **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 Purcell effect



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

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

$$\gamma = \frac{\Gamma_{non\_cav}}{\Gamma_{all}}$$

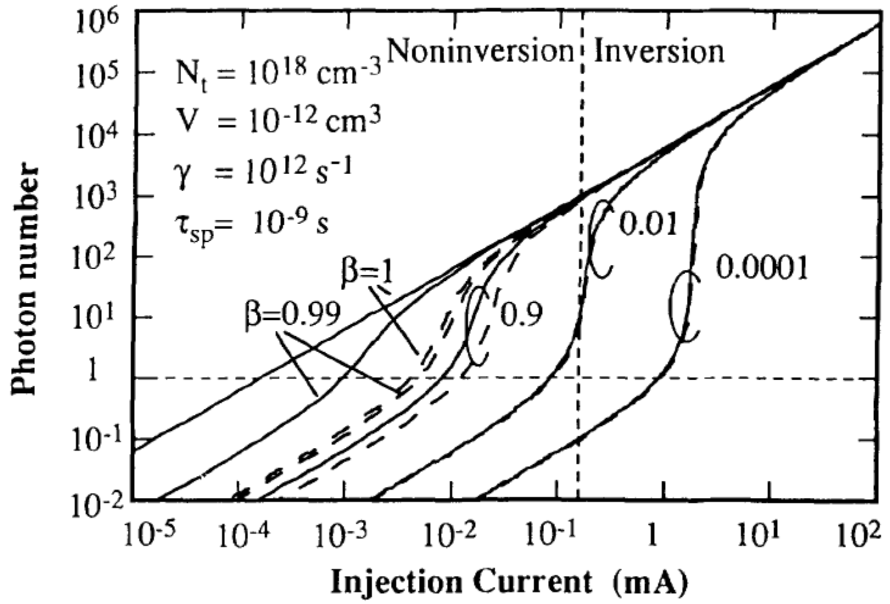
$$\beta = \frac{F_p}{\gamma + F_p}$$

PhC lasers: Static properties

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)

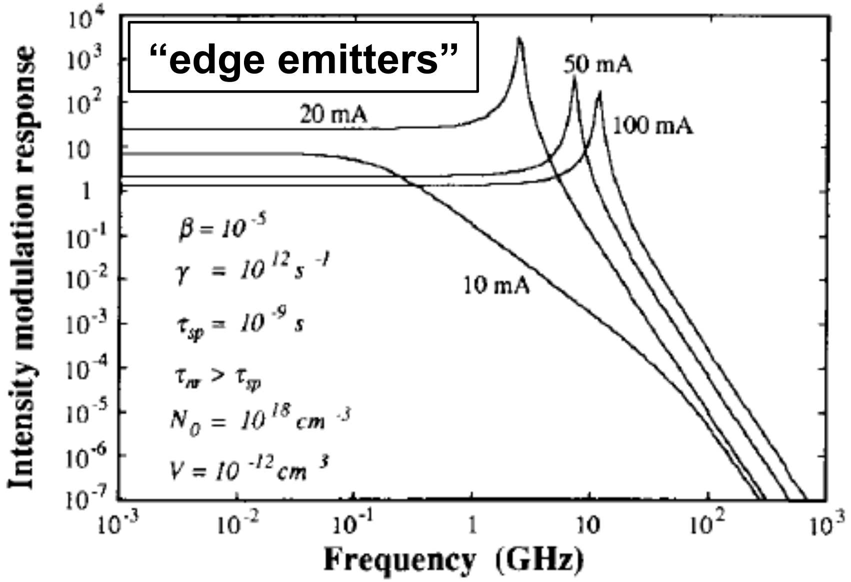
No! New definitions of threshold!
Quantum or statistical definitions

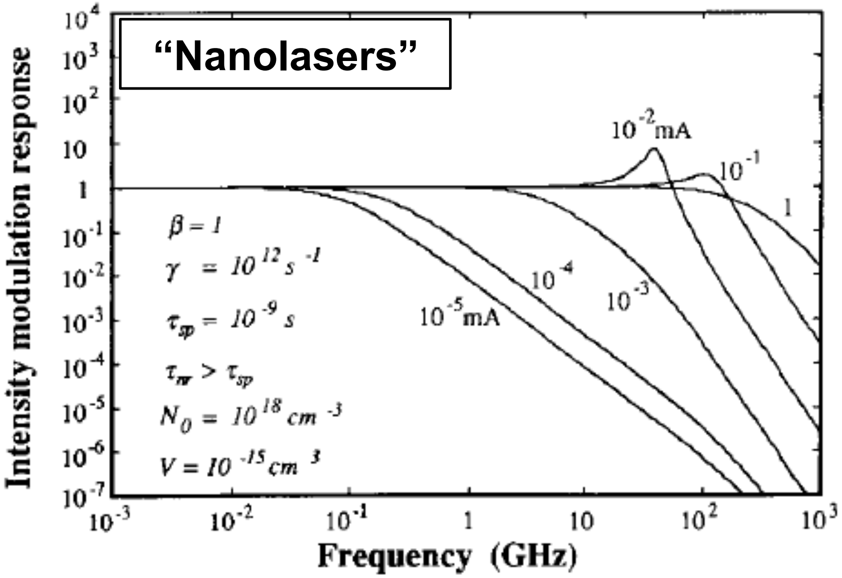
PhC lasers: Dynamics

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!**

cnrs dépasser les frontières

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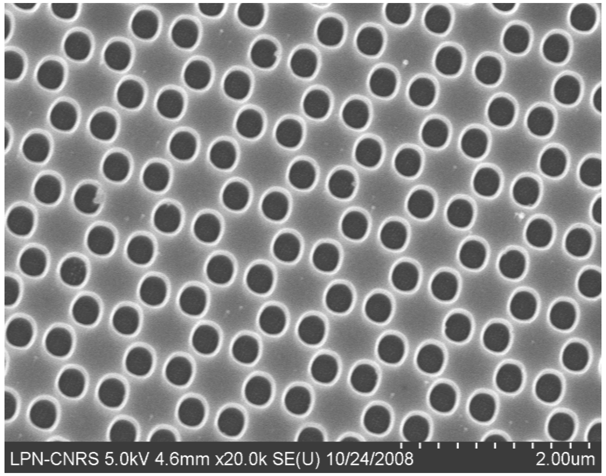
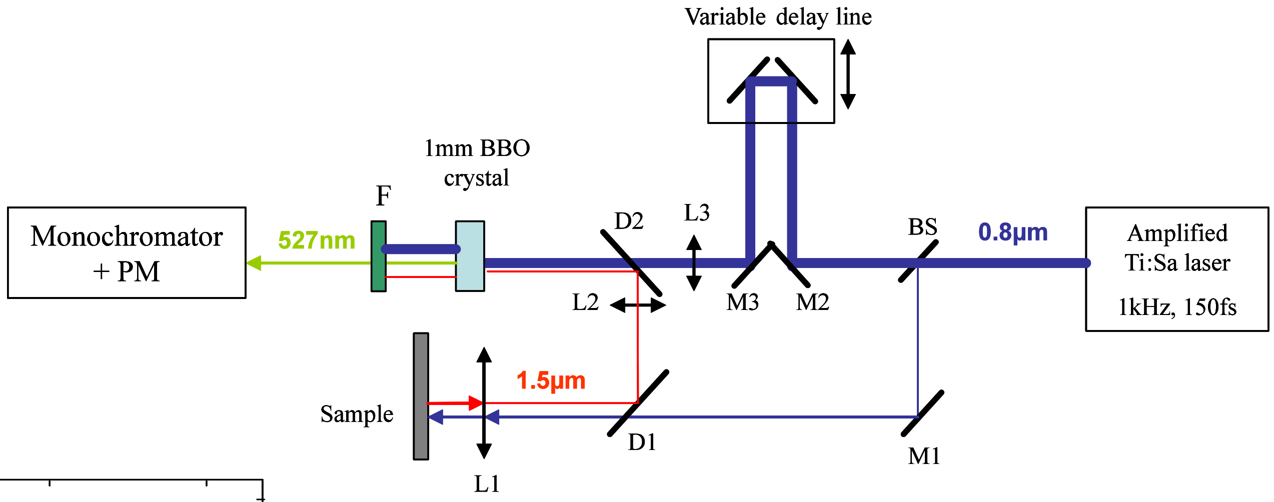
PhC laser: Dynamics

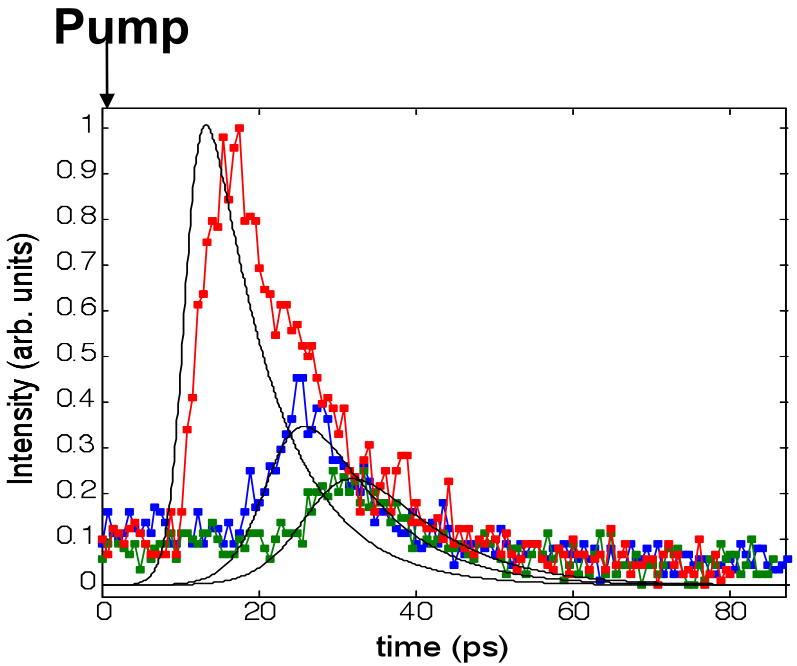
Band edge laser on Si @1.55μm



Some experiments

Up-conversion gating technique





→ **25GHz direct modulation possible**

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

PhC laser: Dynamics

Some experiments on nanocavities

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

950nm Nanocavity laser

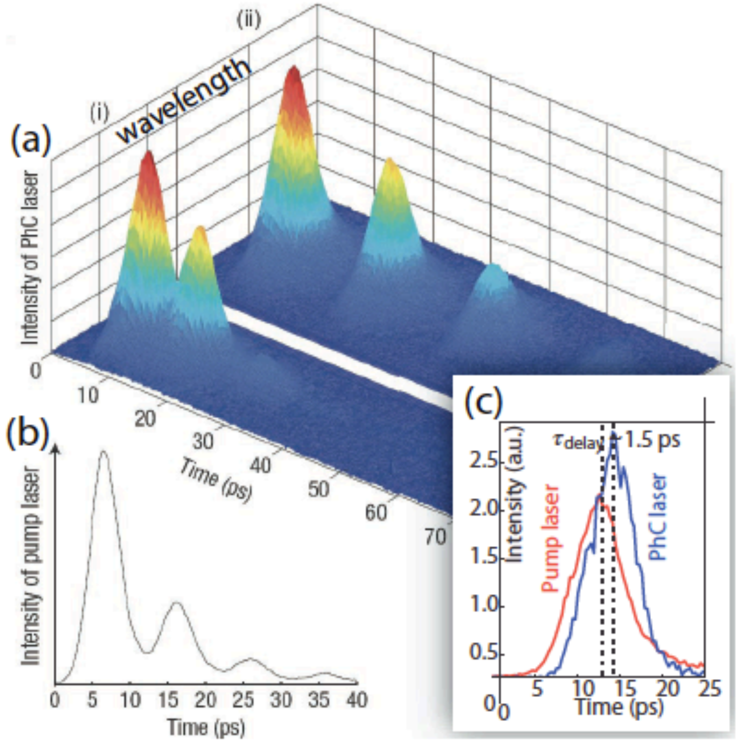


Figure 8 (online color at: www.lpr-journal.org) Large-signal lasing response in QW-driven PC laser. (a) Response to excitation pulses at (i) 9 ± 0.5 and (ii) 15 ps. (b) Excitation pulse train created by etalon setup. Imperfect mirror arrangement causes an exponential decrease in pulse power and only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

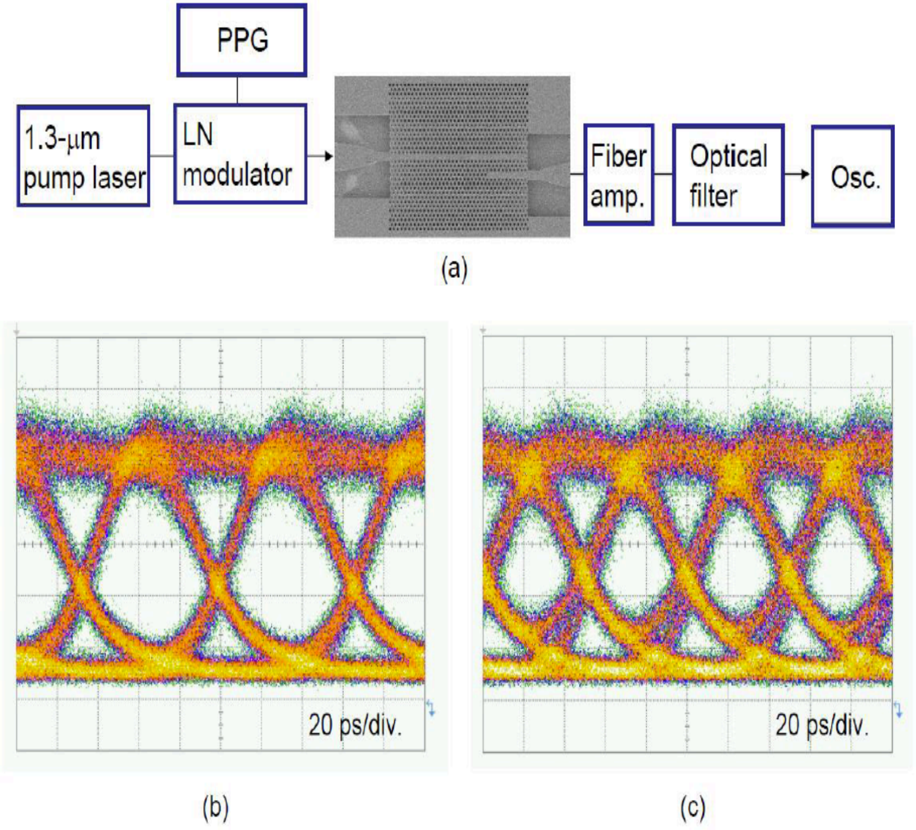
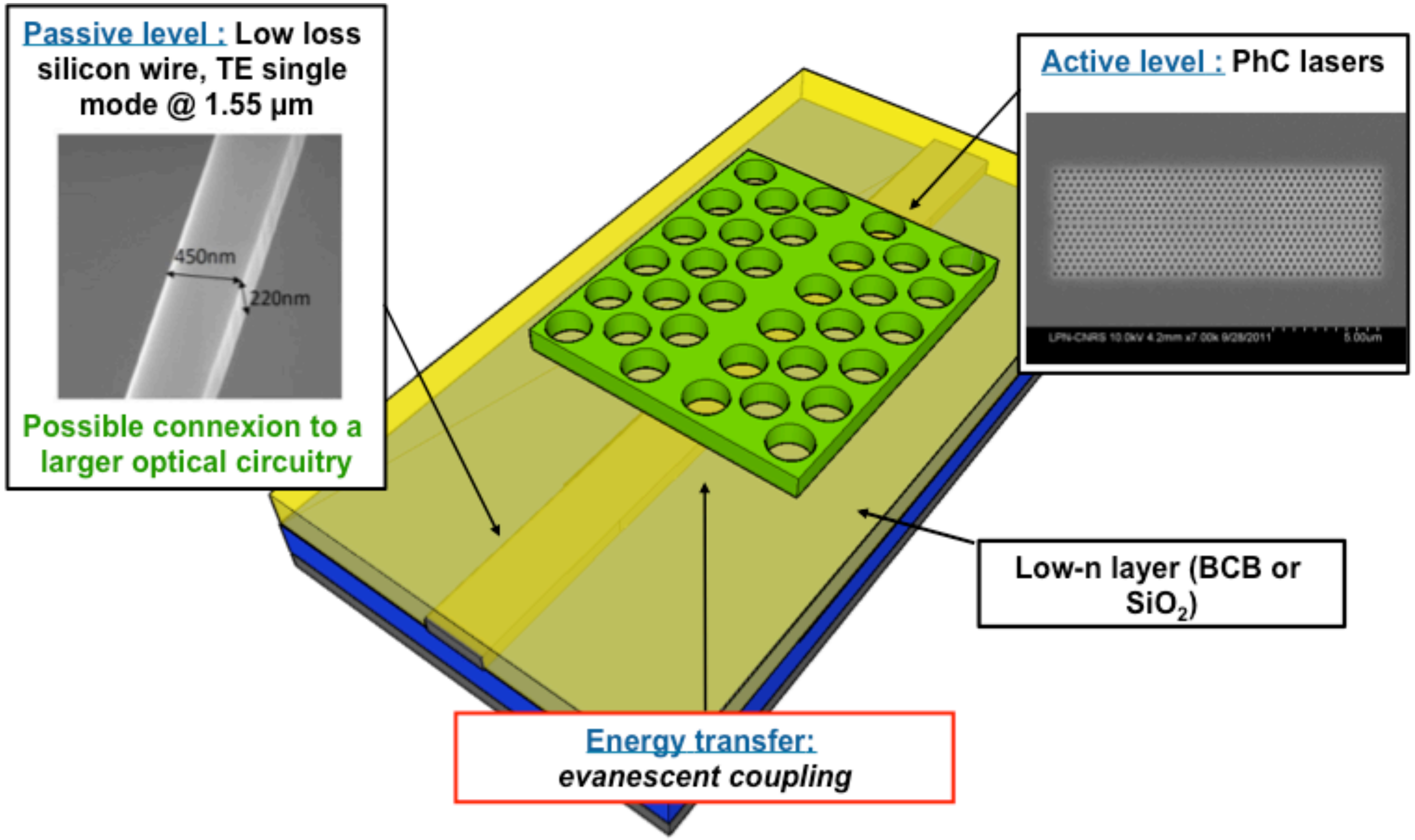


Fig. 6. (a) Experimental setup for direct modulation. Eye diagrams for (b) 15 Gbit/s and (c) 20 Gbit/s NRZ signals.

General view of the hybrid structure: coupling scheme



Passive level : Low loss silicon wire, TE single mode @ 1.55 µm

Possible connexion to a larger optical circuitry

Active level : PhC lasers

Low-n layer (BCB or SiO_2)

Energy transfer:
evanescent coupling

→SMALL FOOTPRINT, ENERGY EFFICIENT AND HIGH SPEED LASERS ON SILICON!

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LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Outline

- Motivations of hybrid photonics and state of the art
- III-V/SOI nanophotonics platform
- Nanolasers efficiently coupled to SOI circuitry

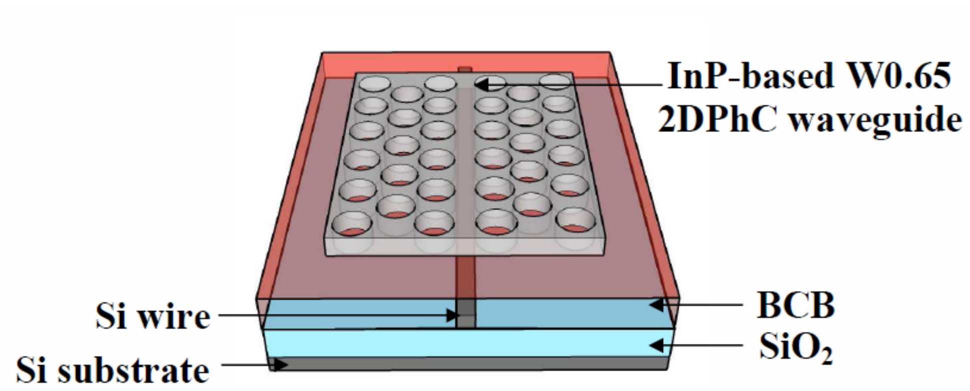
→Evanescent wave coupling

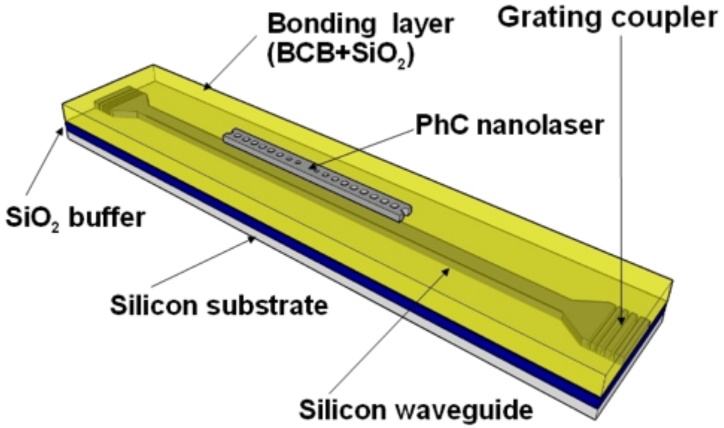
→Fabrication

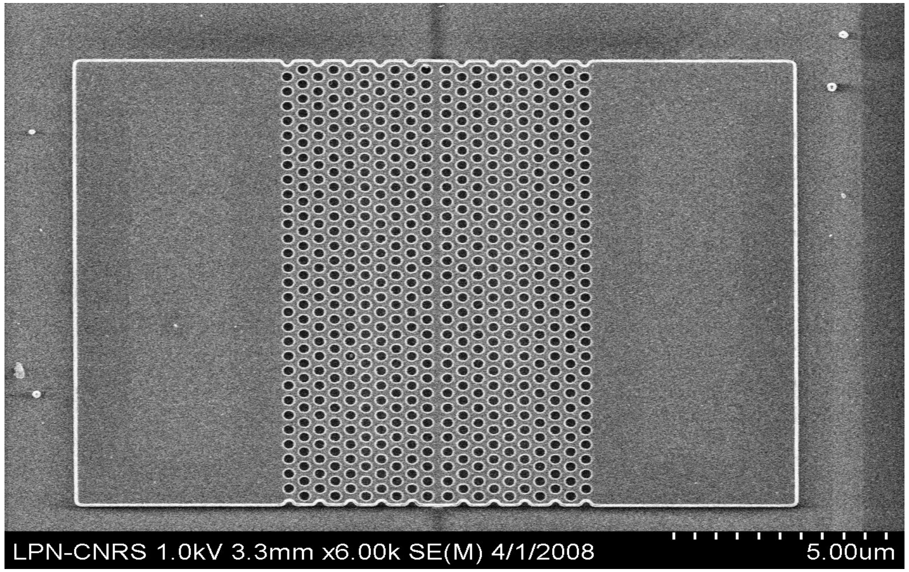
→Experiments

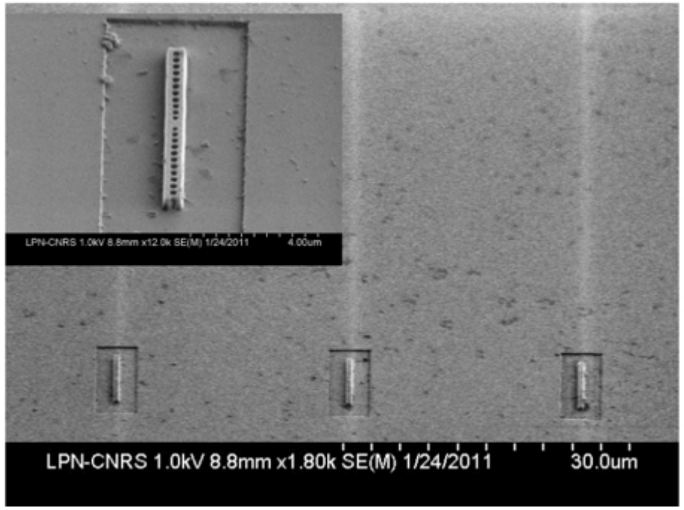
- Hybrid memories and switches

Different type of structures







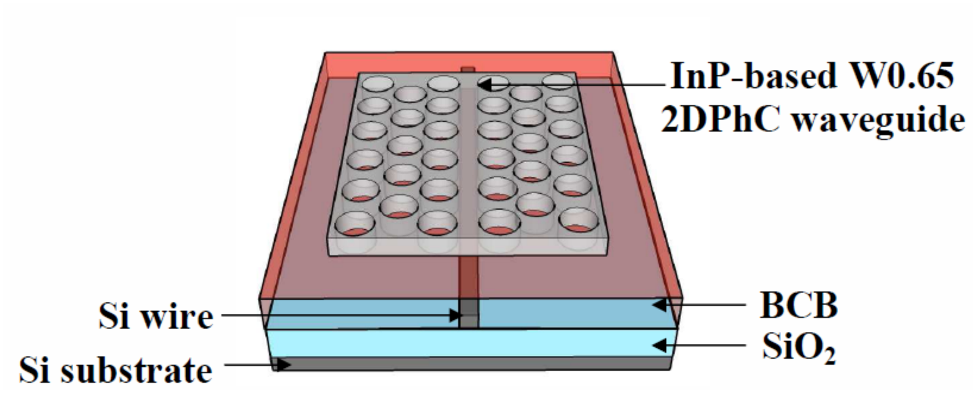


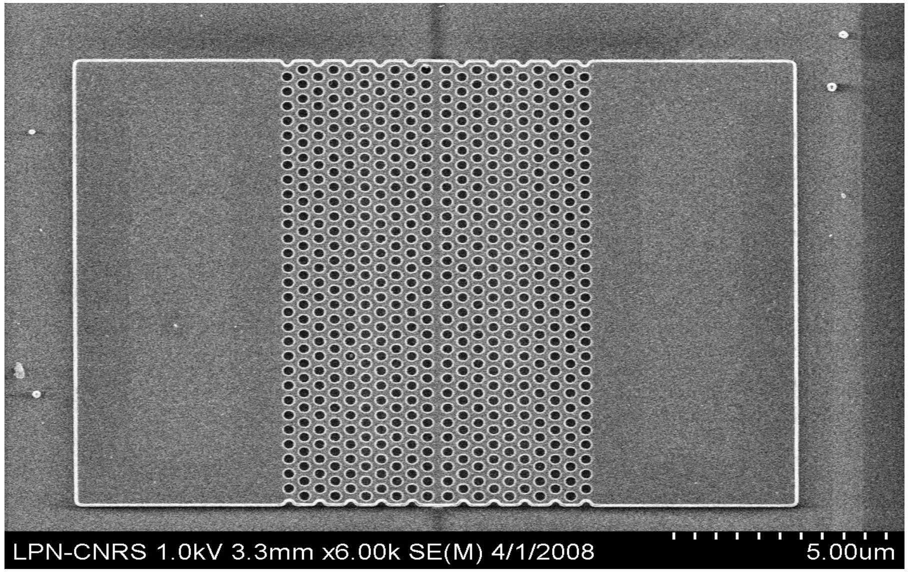
slow light waveguides

Nanocavities

Y. Halioua et al, Appl. Phys. Lett. 95, 201119 (2009)

Different type of structures





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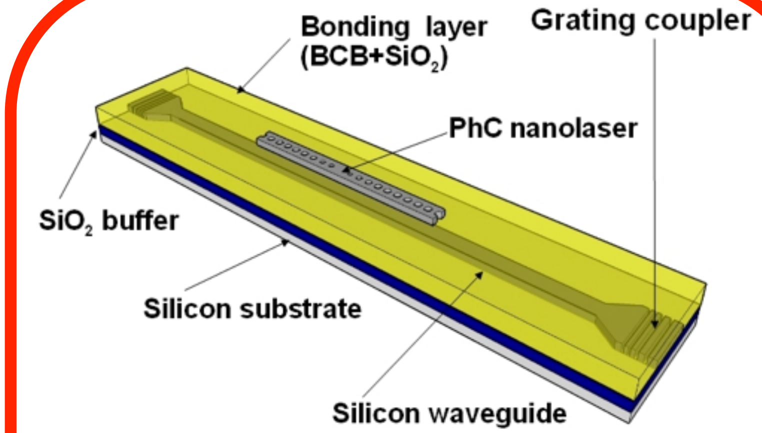
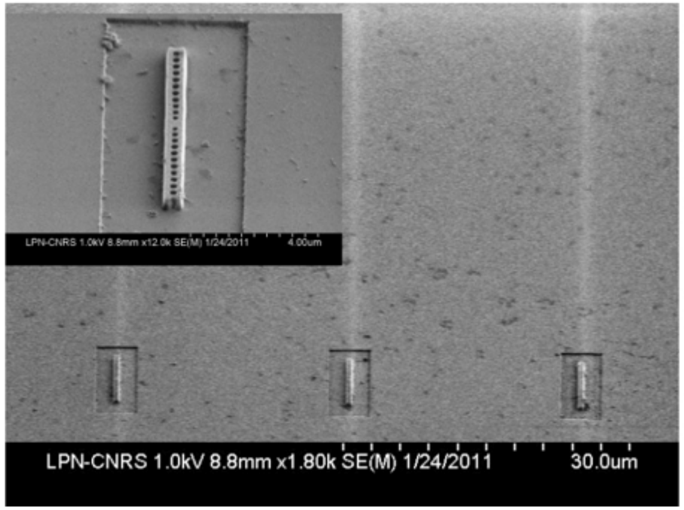


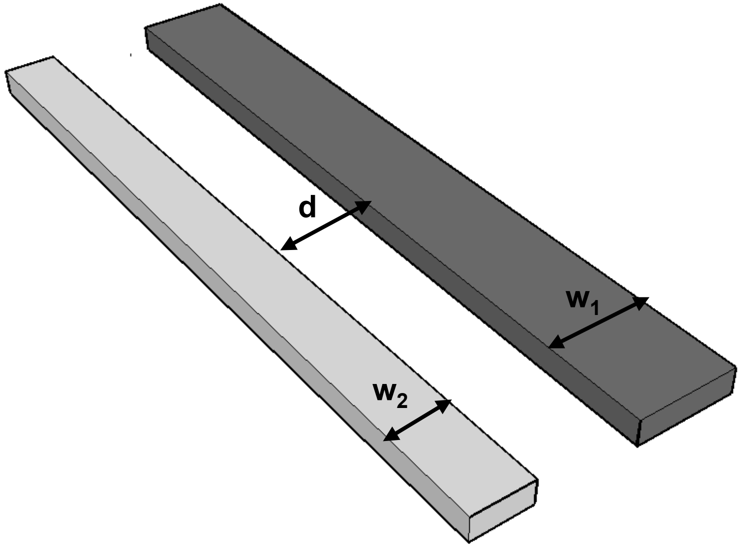


Nanocavities

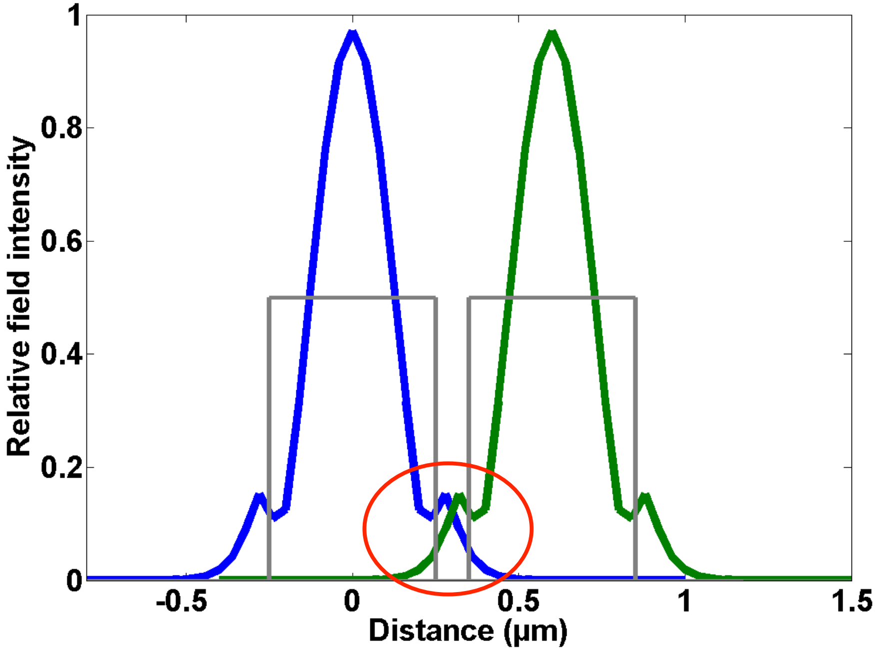
EVANESCENT WAVE COUPLING

Evanescent coupling

Parallel waveguides:



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



Coupling efficiency determined by:

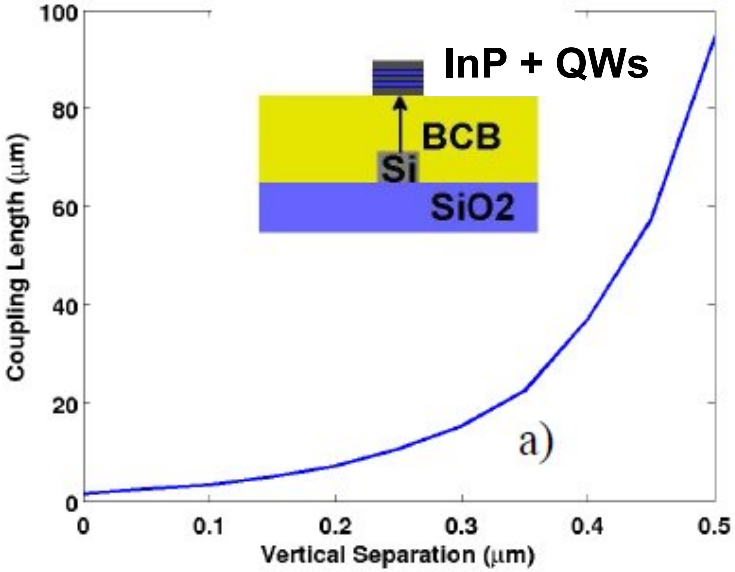
1. **Spatial field overlap** between the original modes
2. **Phase matching** between the original modes

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

Evanescent coupling: field overlap

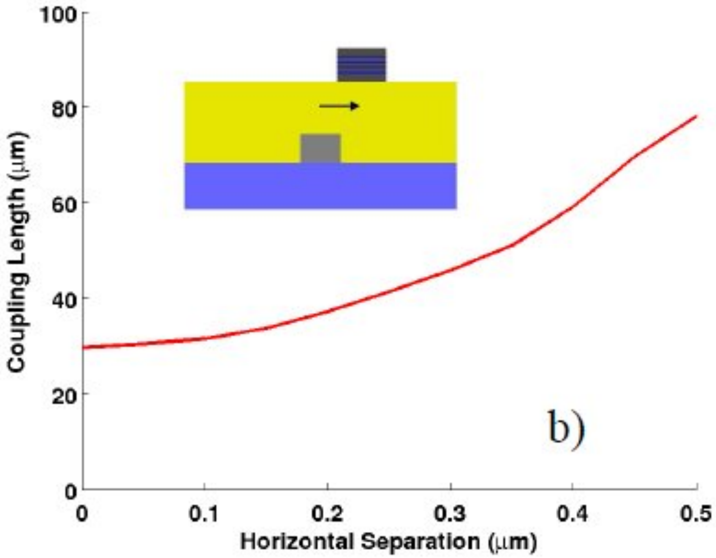
$$L_c \propto \frac{1}{\text{coupling strength}}$$

Vertical separation:



- Exponential dependence in vertical direction
- Evanescent field in BCB ~500 nm

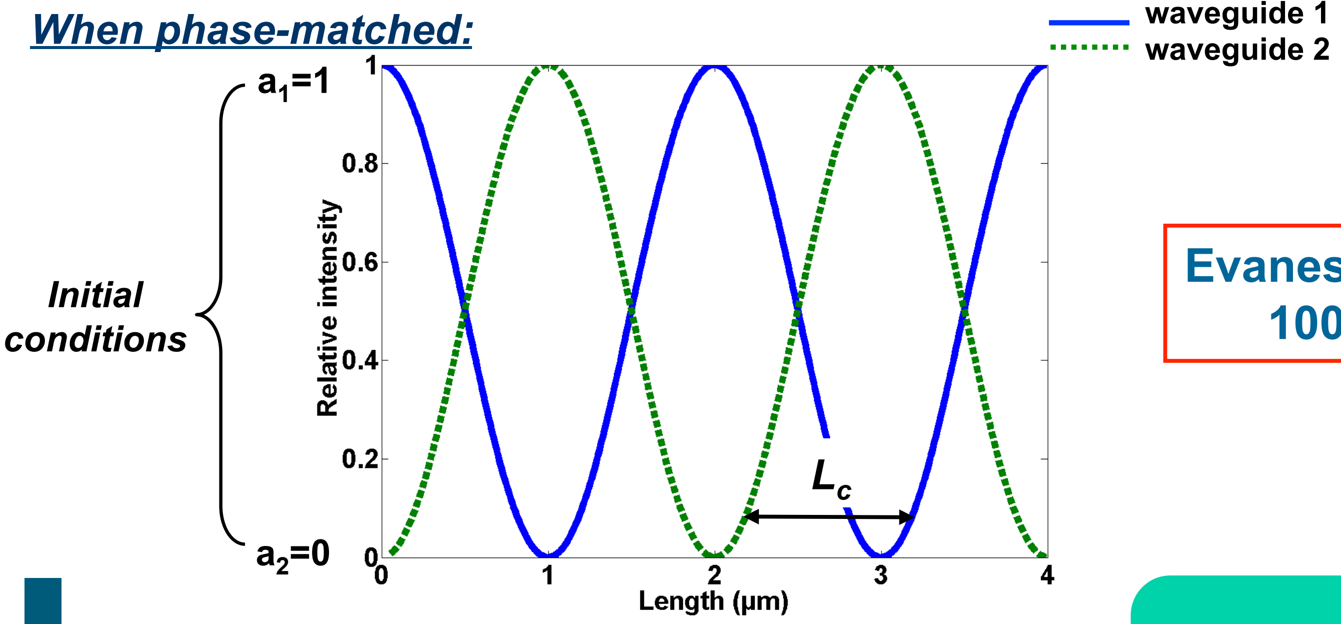
Lateral offset (for 400 nm BCB thickness):



100 nm misalignment gives 15% increase in the coupling length

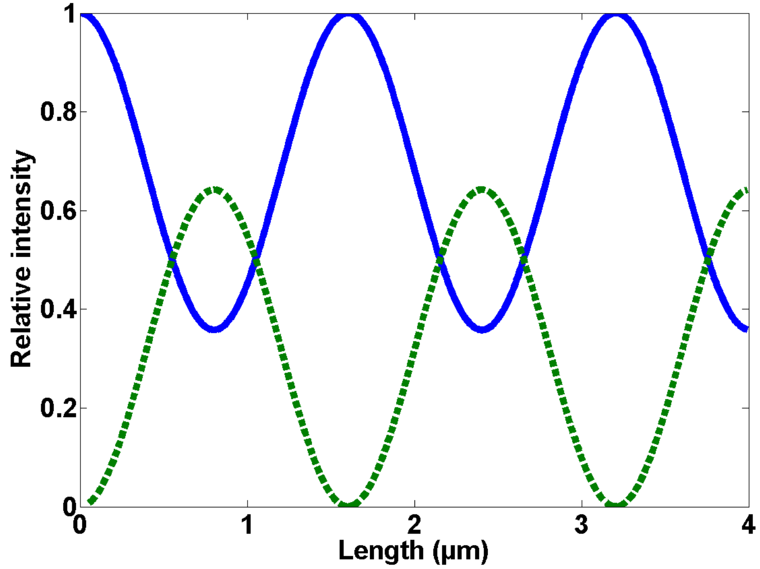
Evanescent coupling: phase matching

When phase-matched:



Evanescent coupling can lead to 100% of energy exchange

When phase-mismatched



For example :

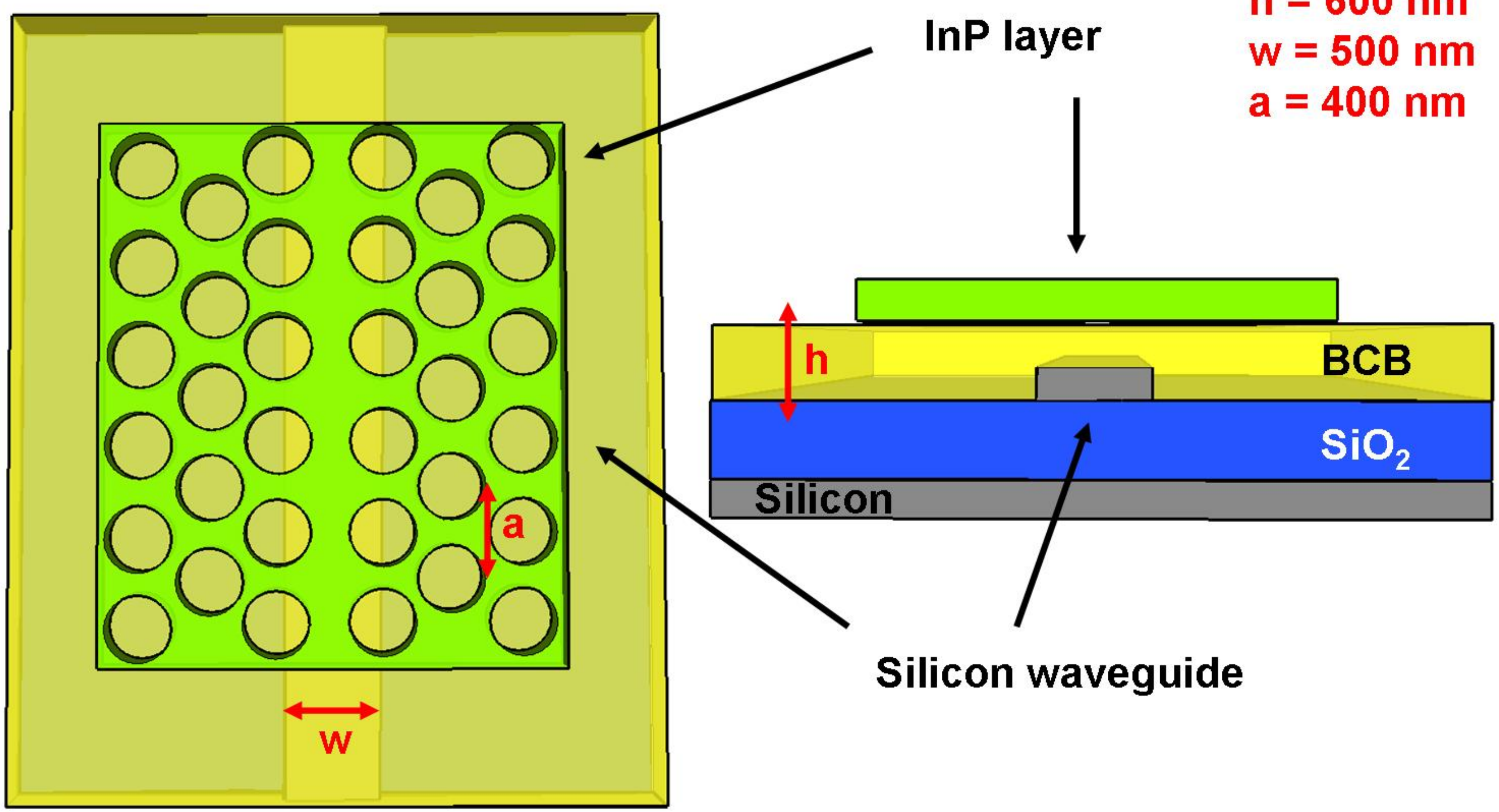
Δn_{eff} = 10 % implies -35% of energy exchanged

Phase matching for hybrid?

- n_{Si} = 3.48, $n_{InP + Qws}$ = 3.3

Impact on Fabrication

Alignment error should be at approximatively 10% of the typical scales
Accurate control of dimensions necessary for phasematching condition



InP layer

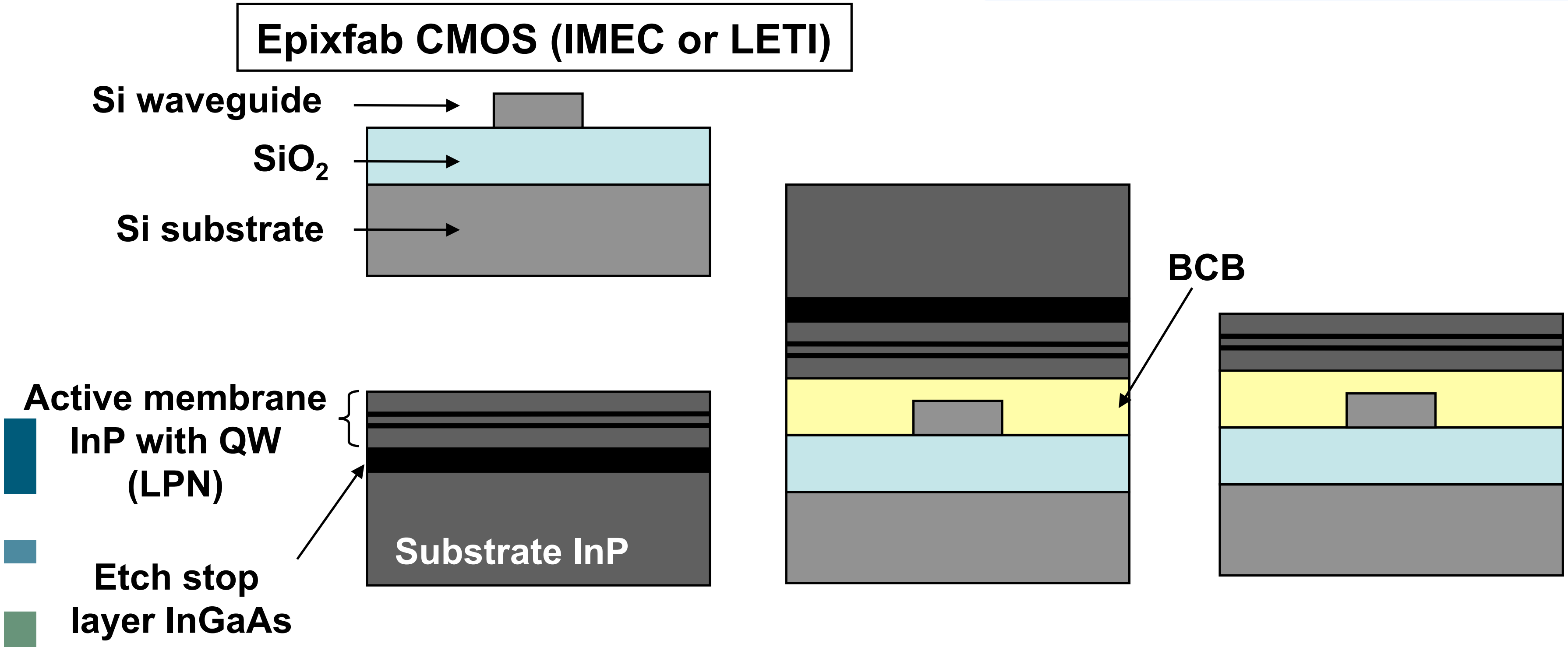
Silicon waveguide

h = 600 nm
w = 500 nm
a = 400 nm

FABRICATION TECHNOLOGY

Fabrication

1- Adhesive bonding



Epixfab CMOS (IMEC or LETI)

Si waveguide

SiO_2

Si substrate

Active membrane InP with QW (LPN)

Etch stop layer InGaAs

Substrate InP

BCB

- BCB dilution in solvent for thickness control (down to 80nm possible!)
- Cleaning of the surfaces, spin coating
- Hard cure for polymerisation

(Gunther Roelkens - Electronics Letters 41(9) p.561-562 – 2005)

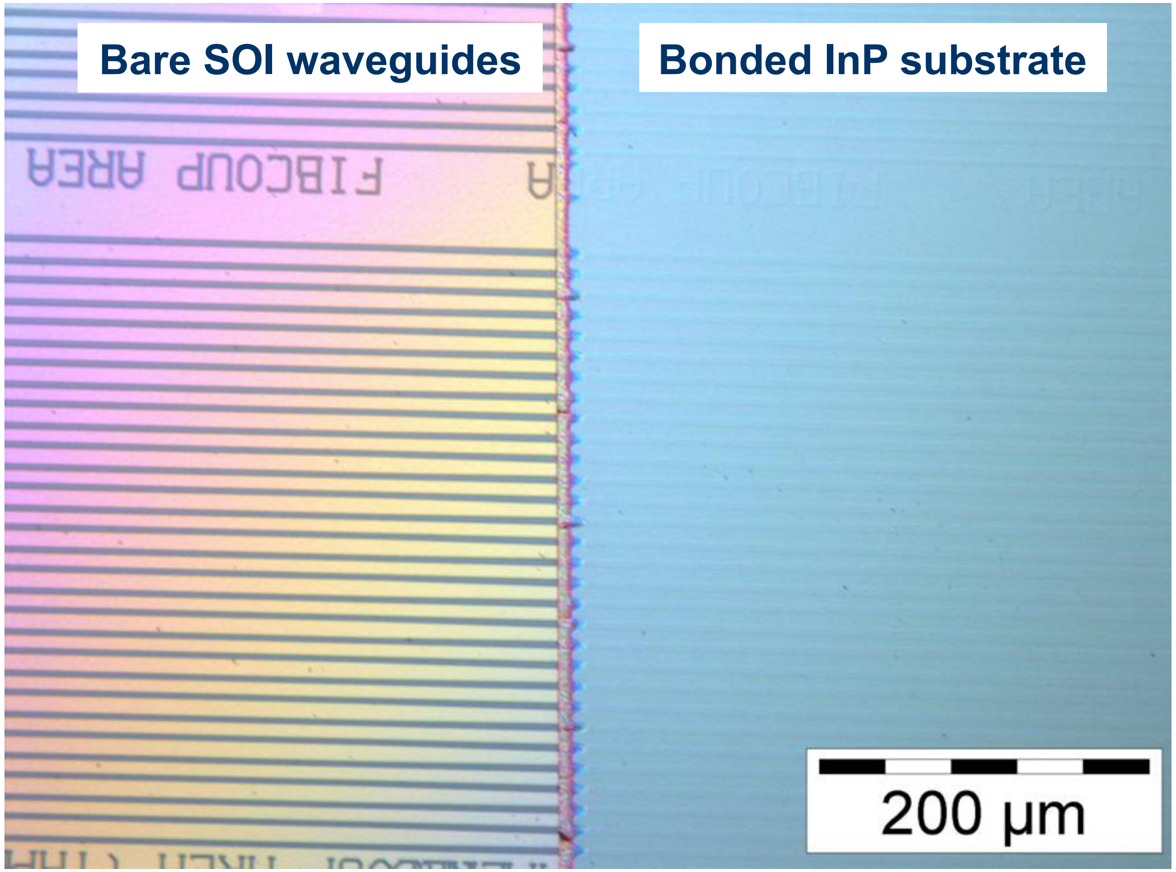
Fabrication

1- Adhesive bonding

Achievements

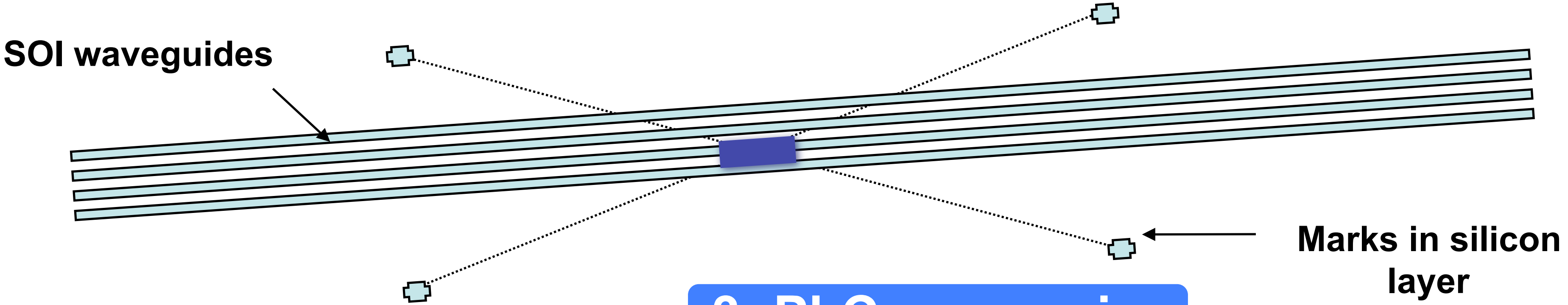
- few cm^2 dyes of InP
- High Yield
- BCB thickness <100nm
- Accurate control of the thickness by SiO2 layer deposition on InP

Typical bonding InP layer on patterned SOI:

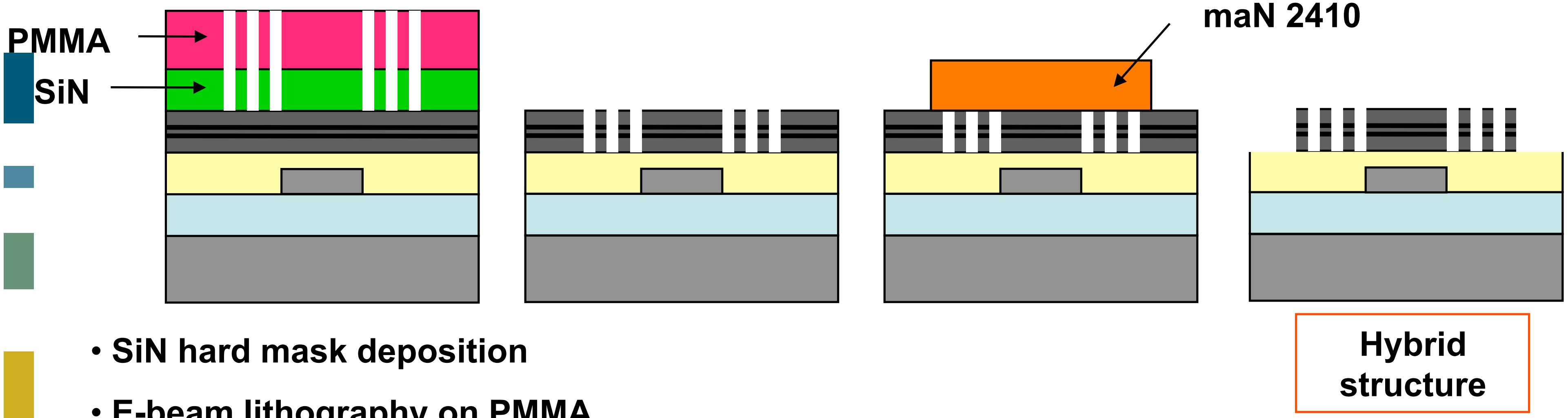


Fabrication

2- Aligned Ebeam lithography

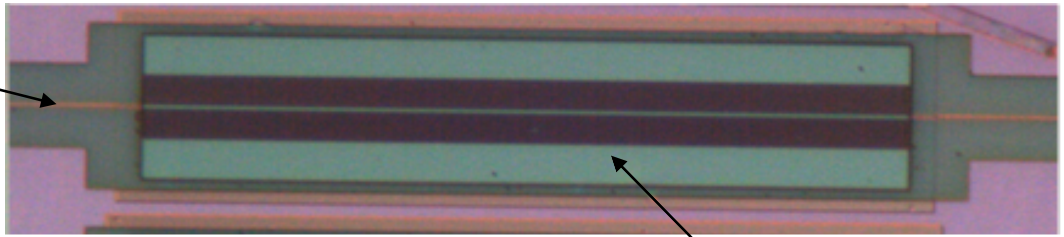


3- PhC processing



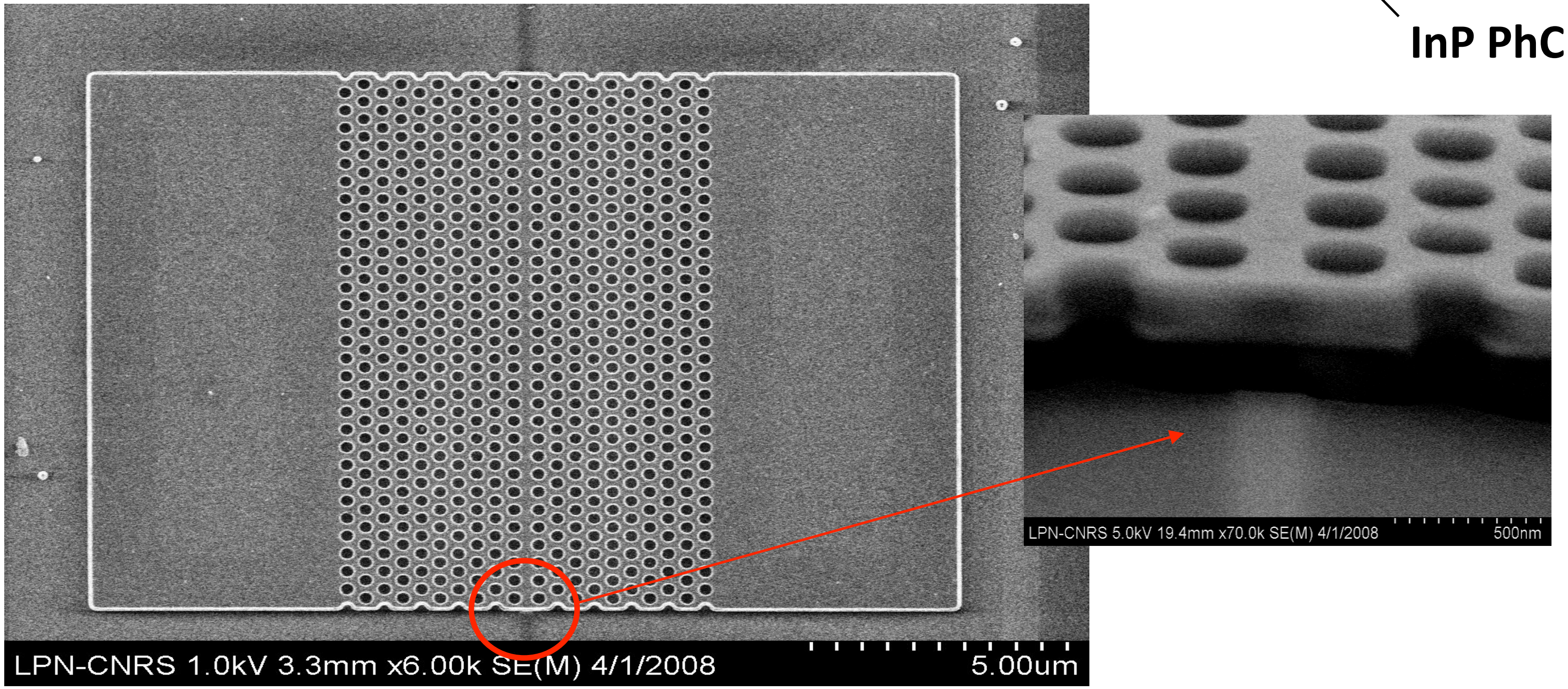
- SiN hard mask deposition
- E-beam lithography on PMMA
- RIE etching of the hard mask
- ICP etching of the InP layer *K.-H. Lee et al J. Vac. Sci. Technol. B 26 (2008).*
- InP removal

Fabrication



Silicon waveguides

InP PhC



Alignment < 30nm → control of evanescent coupling

T. J. Karle et al, J. Appl. Phys 107, 063103 (2010).

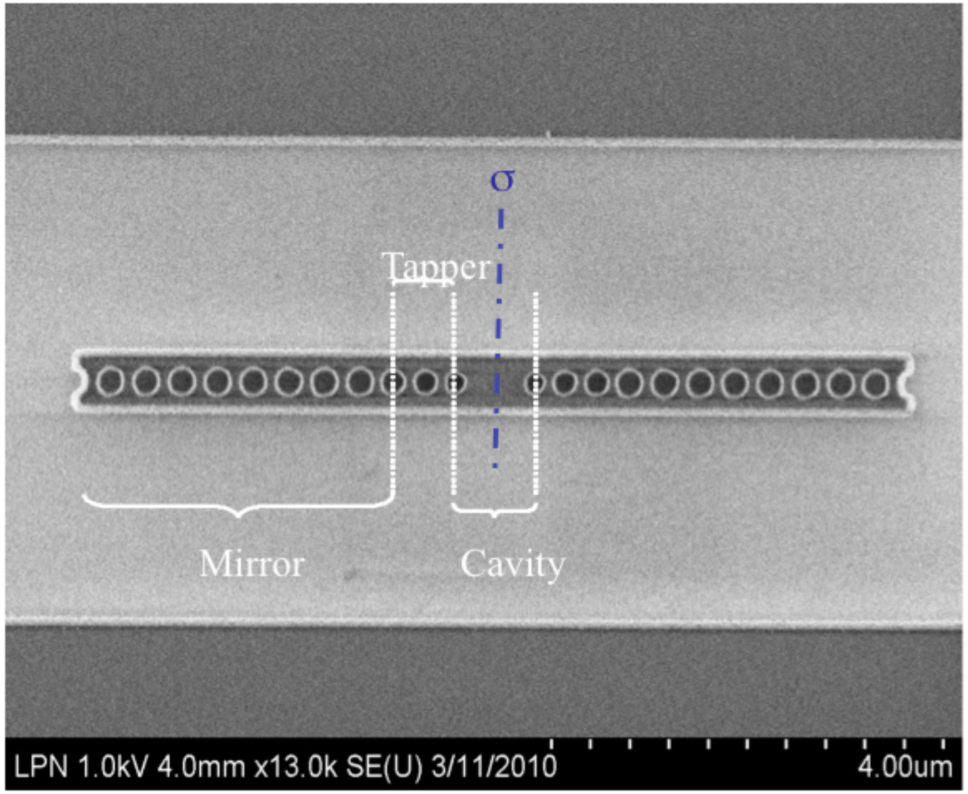
EXPERIMENTAL DEMONSTRATION

Explored sample: Wire cavity

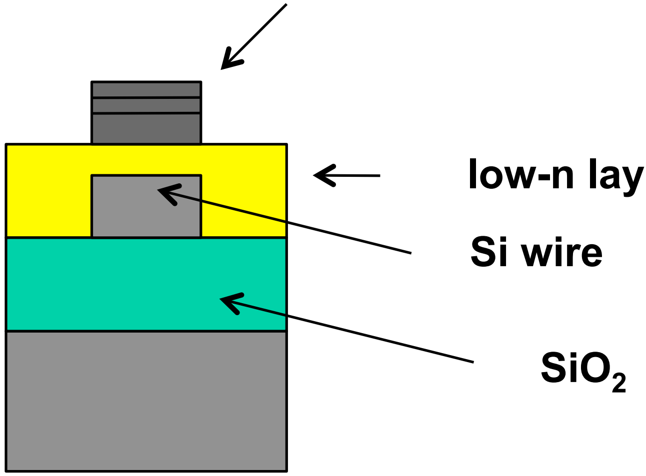
Assets :

- High Q/V on substrate (Q ~ 10^5 demonstrated on SOI)
- Very small footprint (3μm^2)

A. R. Zain, Optics Express, 16 (2008)



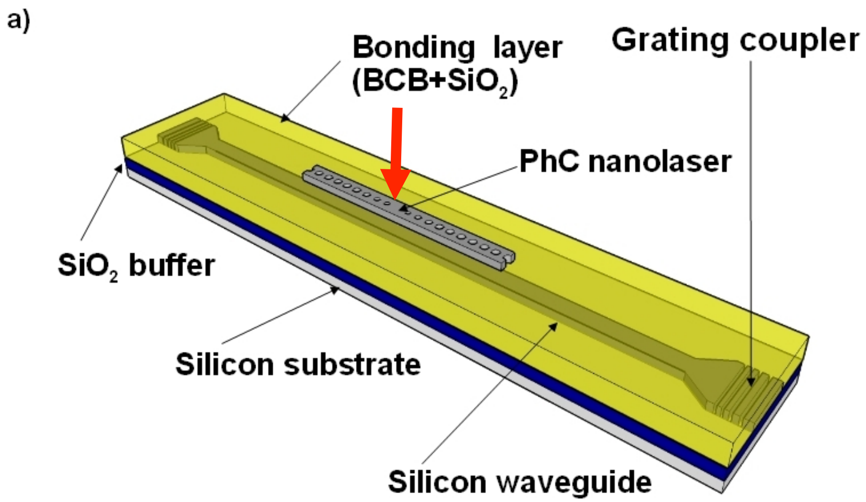
Y. Halioua et al., J. Opt. Soc. Am. B, 27, 2146-2150 (2010)



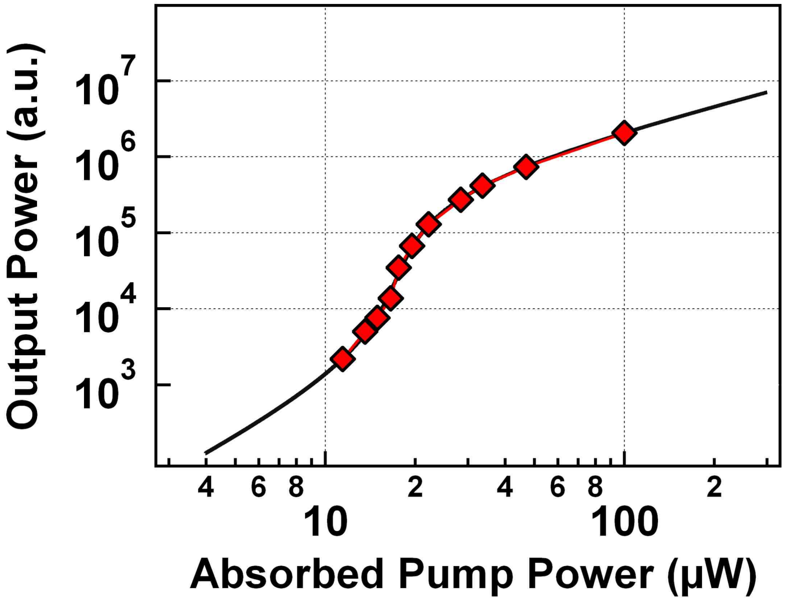
255nm InP membrane + 4 InGaAs/ InGaAsP QWs @1.55μm

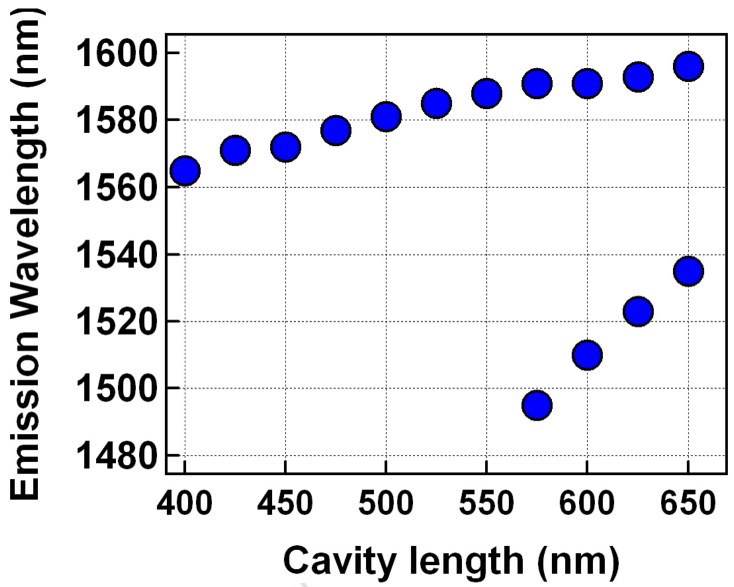
Laser emission

Optical pumping @800nm or 1180nm



→ Threshold around 20µW
→ Control of emission wavelength by tuning the cavity length



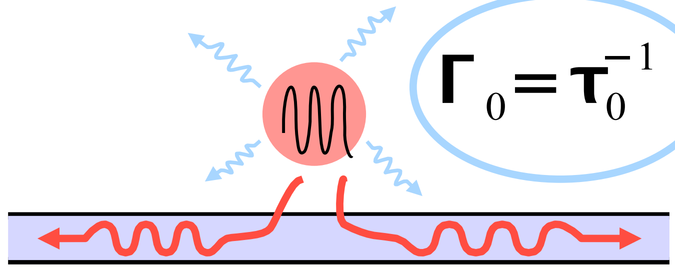


What about coupling efficiency ?

- **Cavity “losses” channels:**

→Intrinsic losses Γ_0 (*uncoupled cavity*)

→Coupling channel Γ_c



$$\Gamma_0 = \tau_0^{-1}$$

$$\Gamma_c = \tau_c^{-1}$$

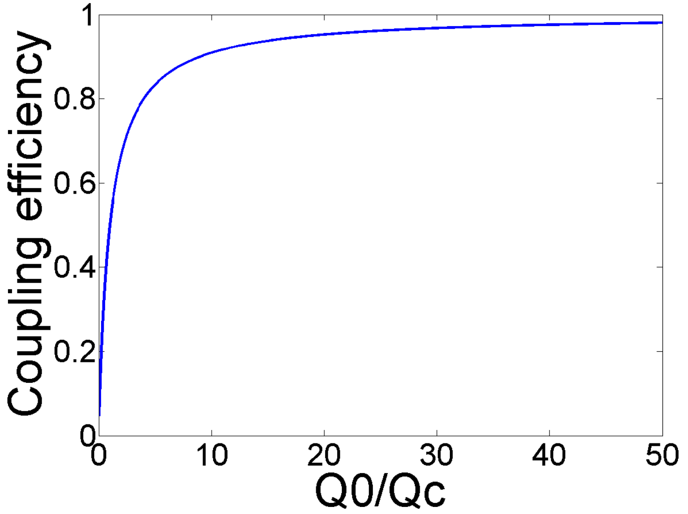
- **Coupling efficiency**

$$\eta = \frac{\Gamma_c}{\Gamma_0 + \Gamma_c} = \frac{Q_c^{-1}}{Q_0^{-1} + Q_c^{-1}}$$

with

$$Q_c \propto \tau'_c$$

$$Q_0 \propto \tau'_0$$



$\eta \approx 90\%$ when $Q_0/Q_c=10$

Coupling between nanolaser and waveguide

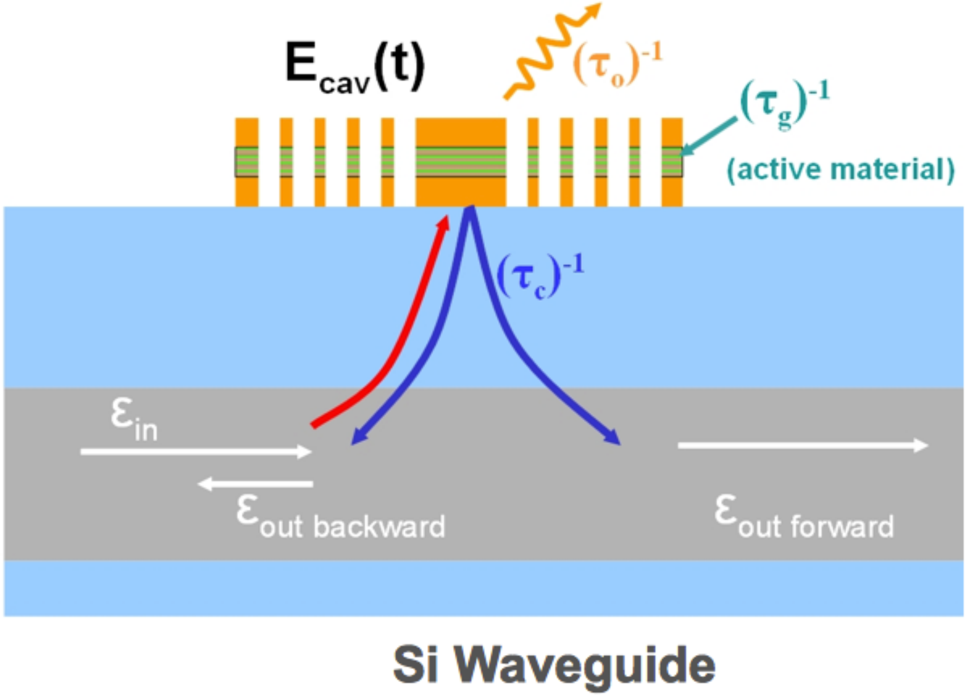
- Laser/waveguide system: intra-cavity field temporal evolution when injected:

$$\boxed{\frac{dE_{cav}}{dt}=\left(j\omega_0-\frac{1}{\tau_c}-\frac{1}{\tau_0}+\frac{1}{\tau_g}\right)E_{cav}+\sqrt{\frac{1}{\tau_c}}\varepsilon_{in}}$$

absorption/gain « losses »

$$\frac{1}{\tau_g}=+\Gamma v_g\sigma(N-N_{tr})\Big/2$$

→Tunable parameter



Transmission of an incoming wave in the waveguide

$$T=\left|\frac{\epsilon_{out\ forward}}{\epsilon_{out\ input}}\right|^2$$

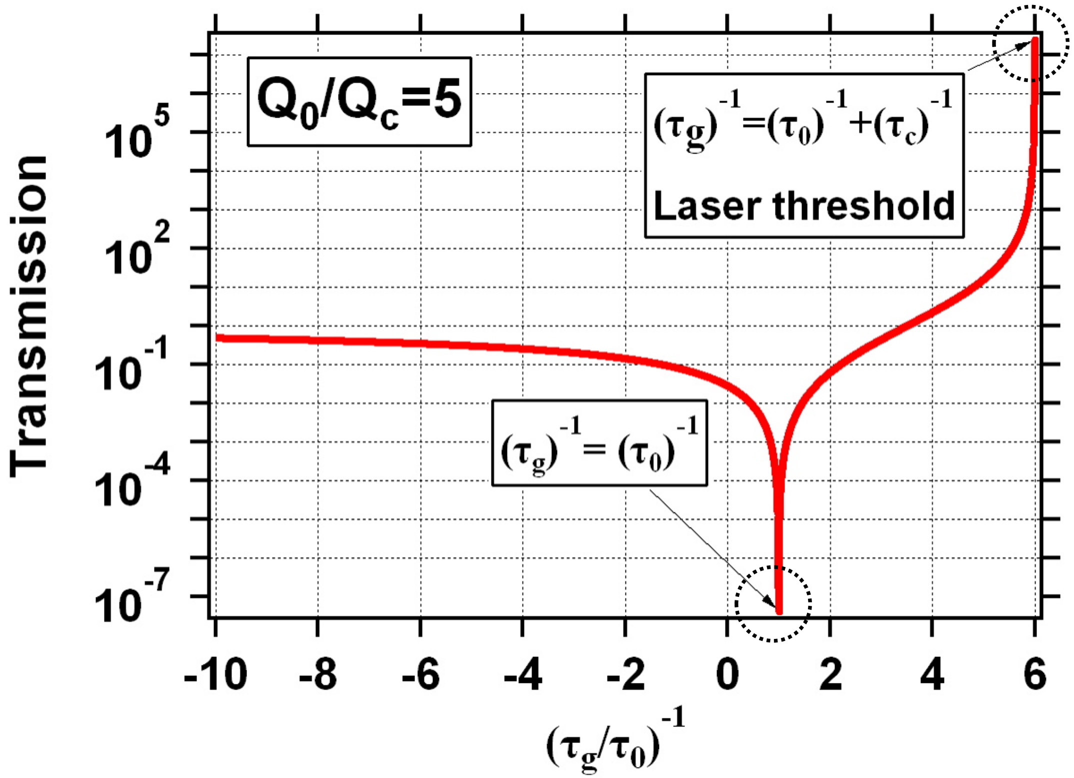
Coupling between laser cavity and waveguide

- **Coupled mode theory applied for a cavity coupled to a waveguide**

$$T(\omega)=\left|1-\frac{\frac{1}{\tau_c}}{j(\omega-\omega_0)+\frac{1}{\tau_c}+\frac{1}{\tau_0}-\frac{1}{\tau_g}}\right|^2$$

C. Manoulatou et al.,IEEE JQE 35,1322-1331(1999)

+ Absorption/Gain



- T=0 when gain compensates intrinsic losses:

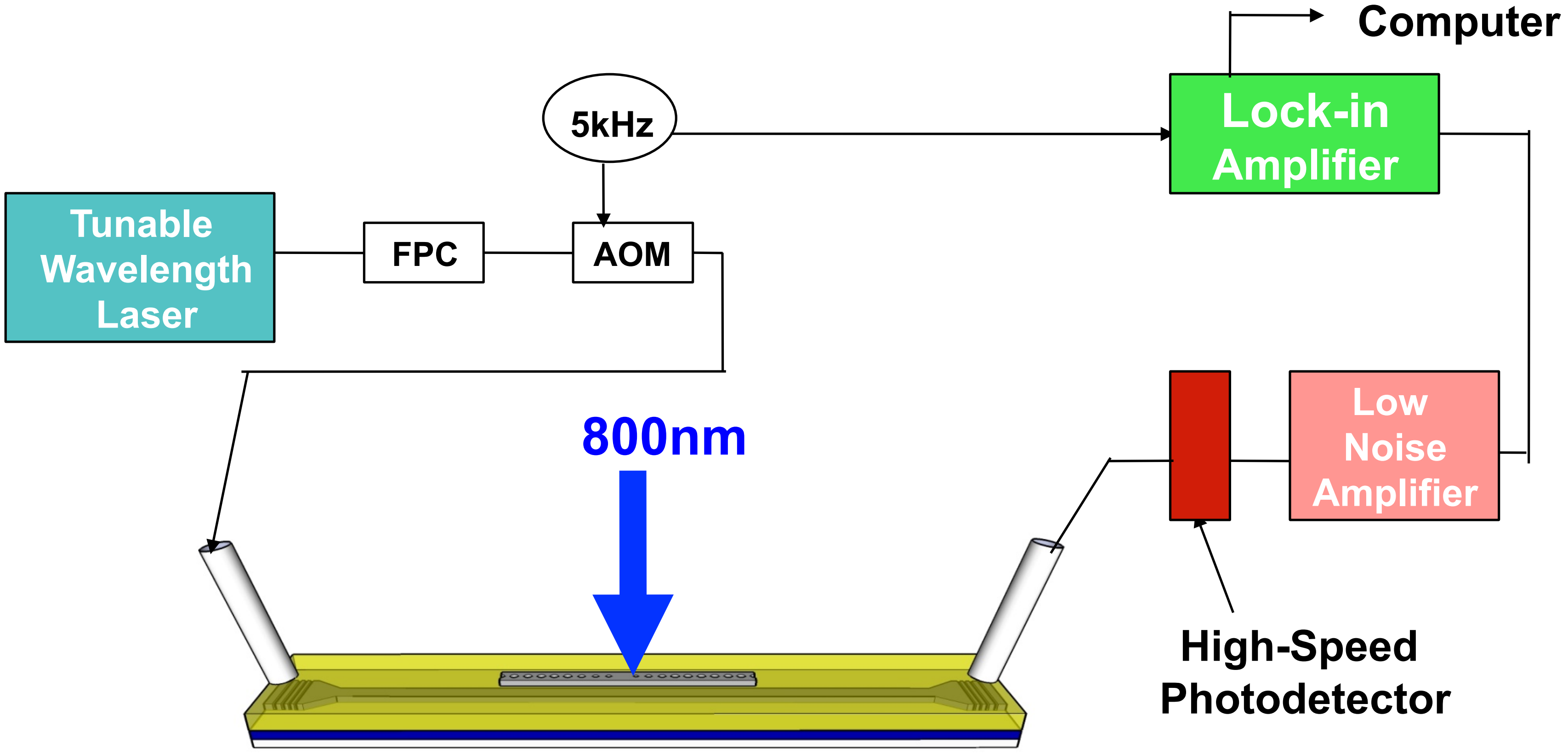
FWHM gives τ_c

- At laser threshold

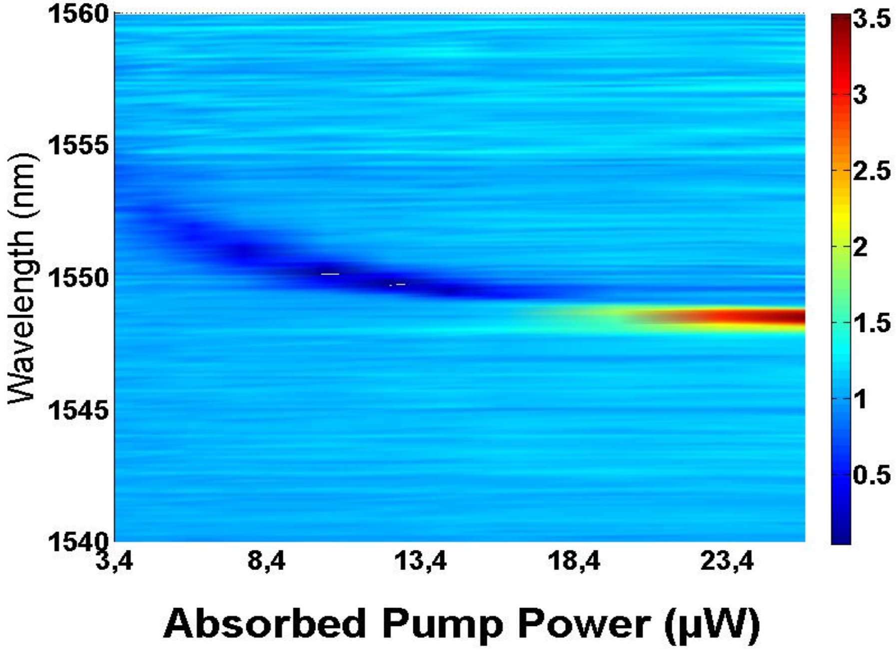
gain compensates all losses

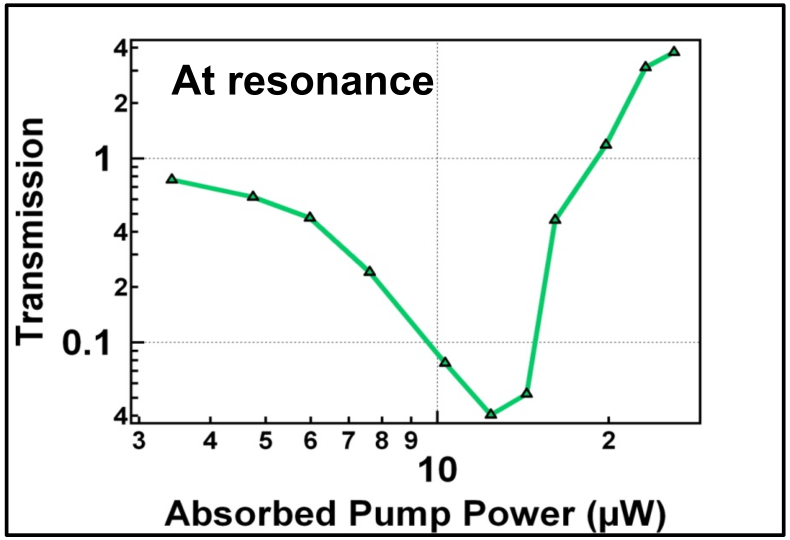
Experimental set-up

- Goal: measure transmitted spectra through the WG around resonance of the laser

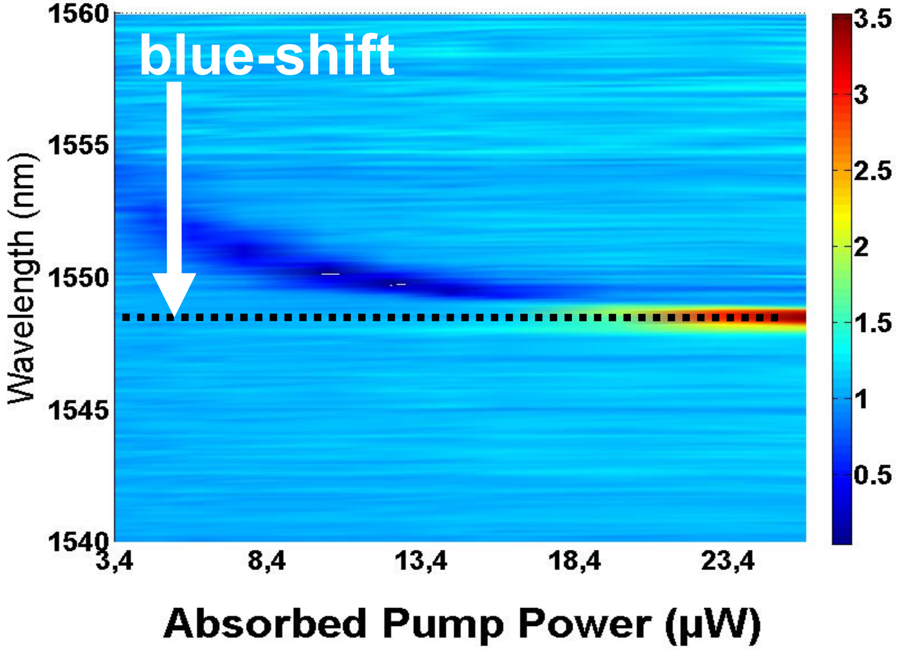


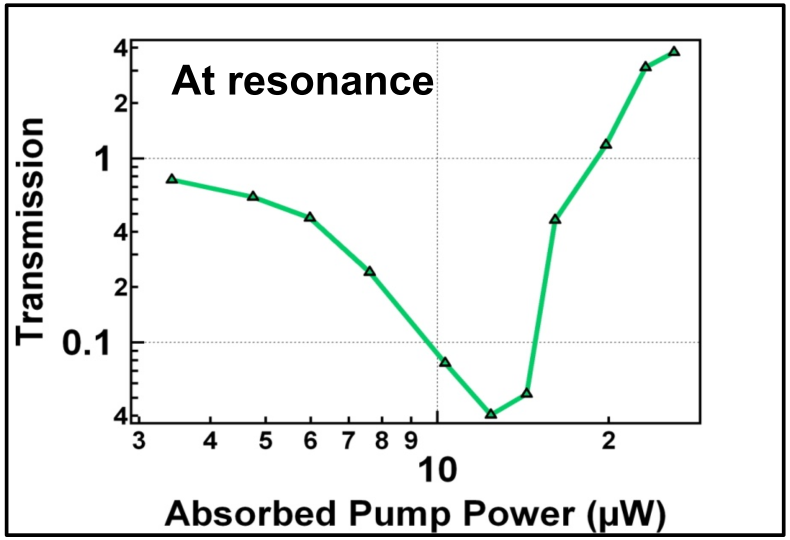
Pump-Probe transmission measurement





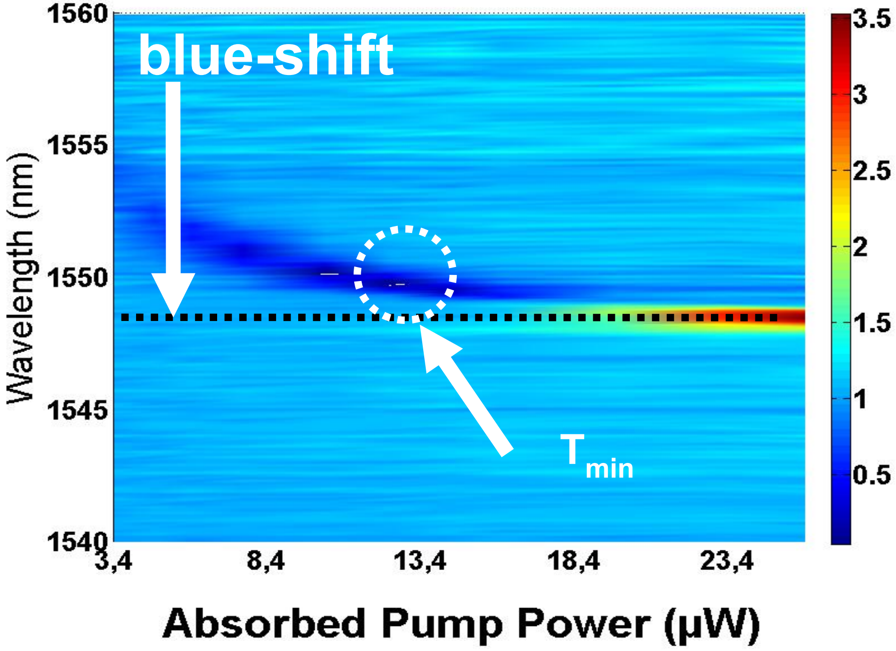
Pump-Probe transmission measurement

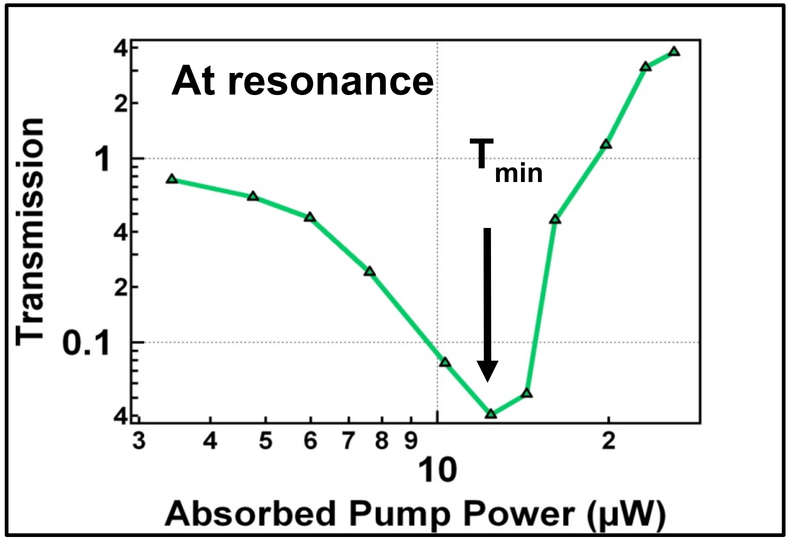




- Index changes with carrier population (blue-shift)

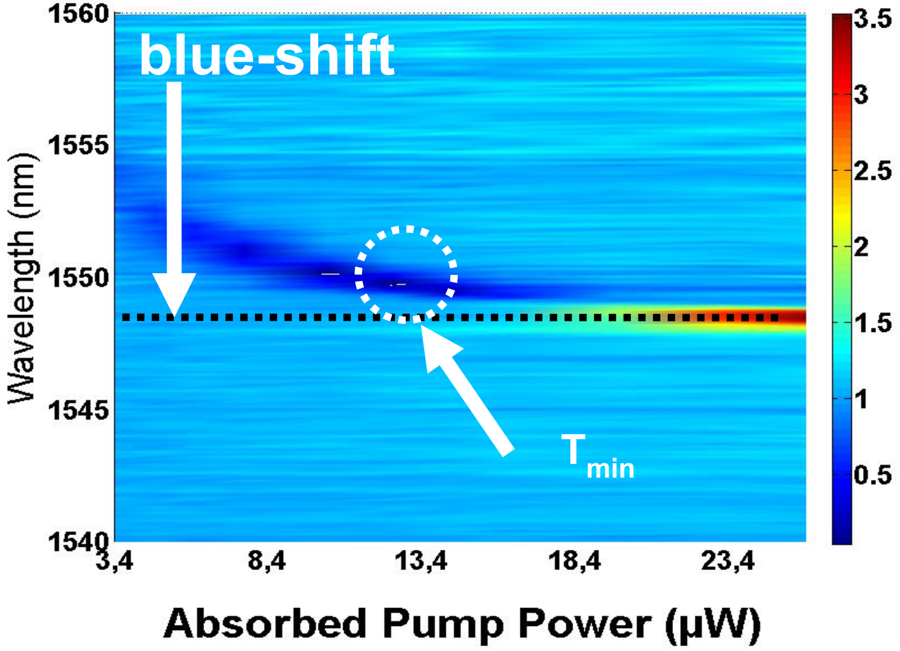
Pump-Probe transmission measurement

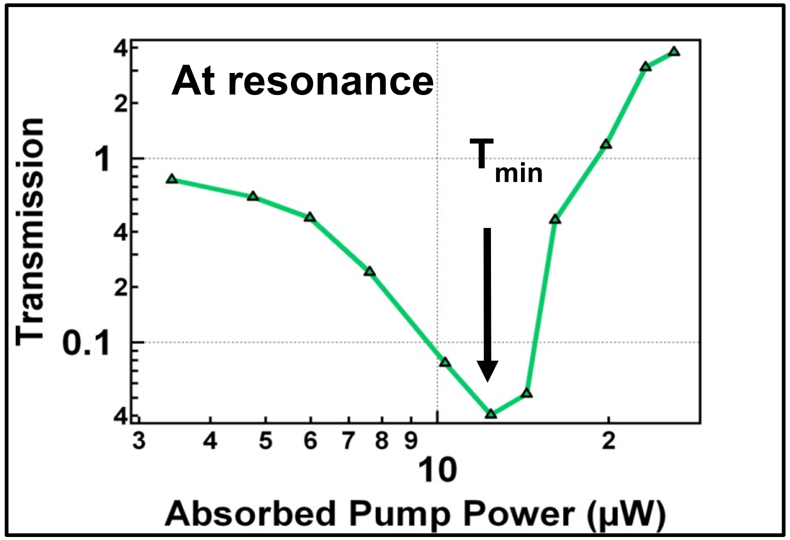




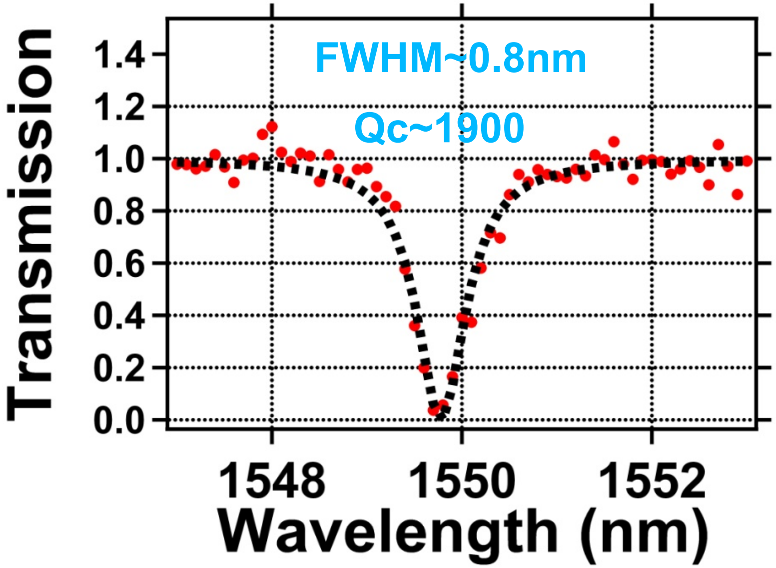
- Index changes with carrier population (blue-shift)
- Minimum of transmission when gain compensates intrinsic losses

Pump-Probe transmission measurement





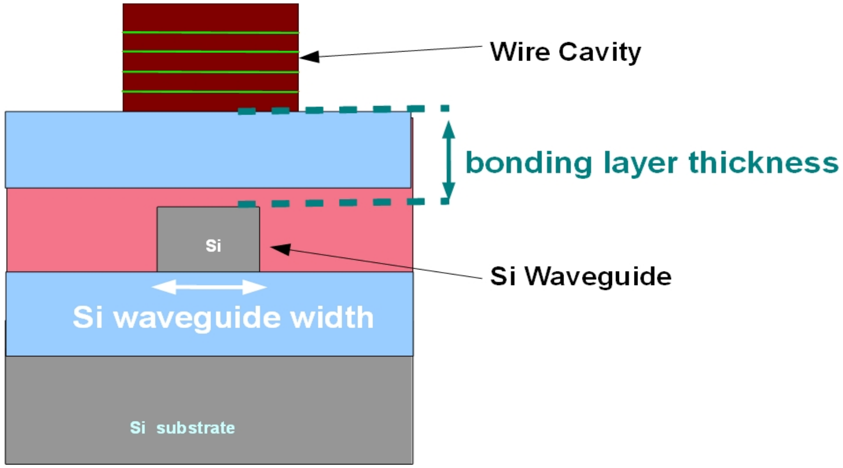
- Index changes with carrier population (blue-shift)
- Minimum of transmission when gain compensates intrinsic losses
- Fit of the transmission spectra at minimum gives:



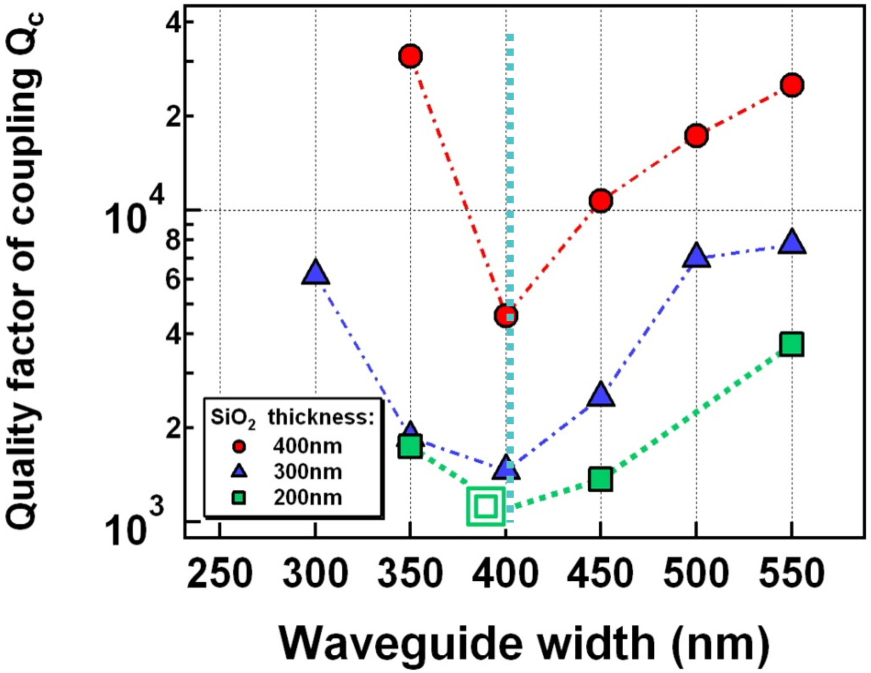
dépasser les frontières

LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Q_c measurements



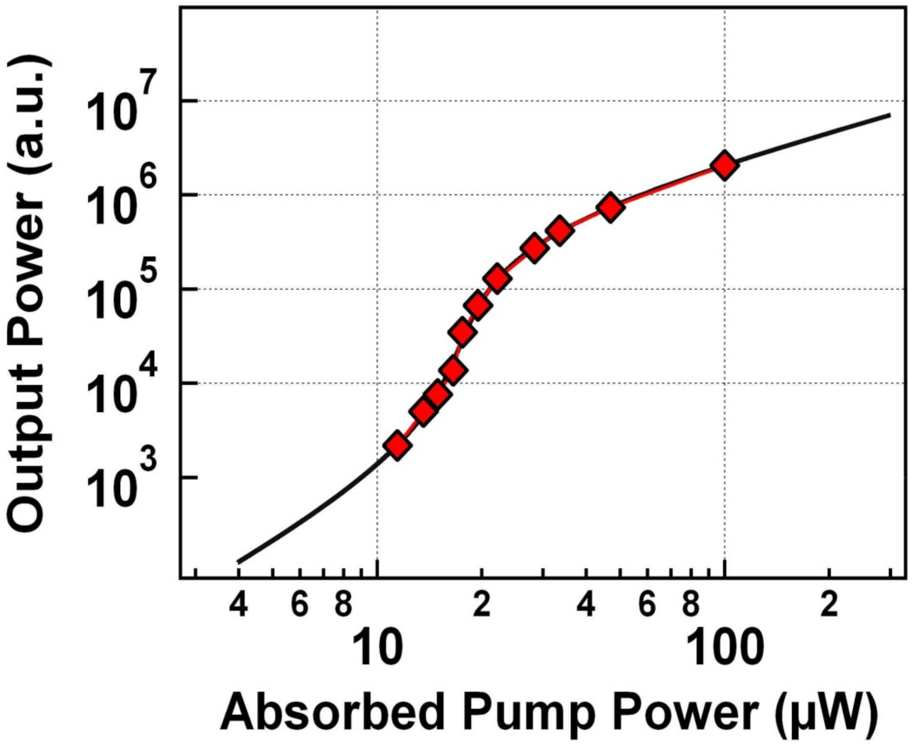
- measurement for cavities coupled to waveguides :
  - with various widths
  - for 3 different separations layer thicknesses.



- Coupling is optimal when overlap in the k-space between waveguide mode and cavity mode is the highest.

$1000<Q_c<30000$

Determination of Q_0



- Uncoupled cavity quality factor Q_0 is necessary to retrieve η

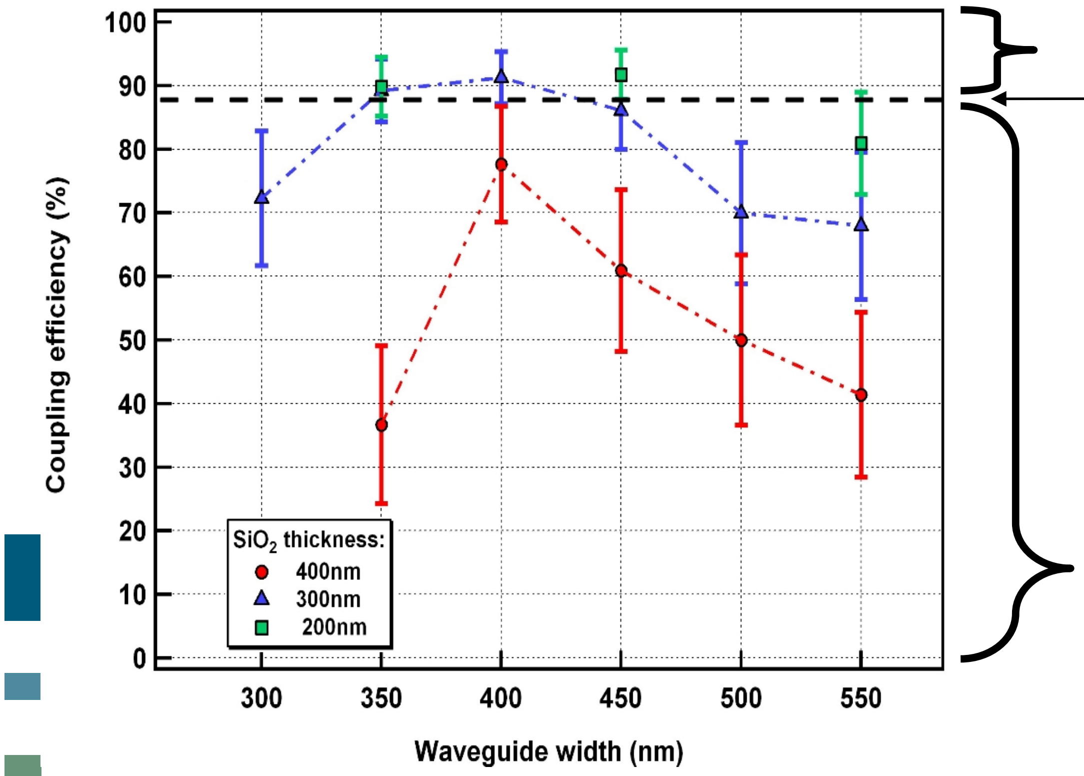
- Standard rate equations for QWs laser are used to fit L-L curve with 2 free variables:

  β factor

  Photon-lifetime

→ $10000<Q_0<30000$

Coupling efficiency



Halioua et al, Opt. Express 19, 9221 (2011)

Total losses > Maximum gain

Boundary of laser emission

Total losses < Maximum gain

Coupling efficiency > 90%

→Very efficient coupling

→ very efficient way to interface PhC cavities

Outline

- Motivations of hybrid photonics and state of the art
- III-V/SOI nanophotonics platform
- Nanolasers efficiently coupled to SOI circuitry
- Hybrid memories and switches

→Bistable injected lasers

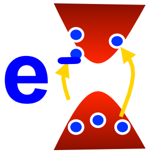
→10Gbits/s switches

- Conclusion and Future Work

LABORATOIRE
DE PHOTONIQUE
ET DE NANOSTRUCTURES

Operation based on active material

III-V quantum wells are embedded as active medium

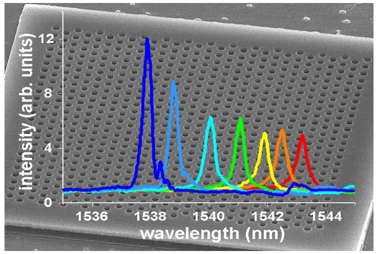


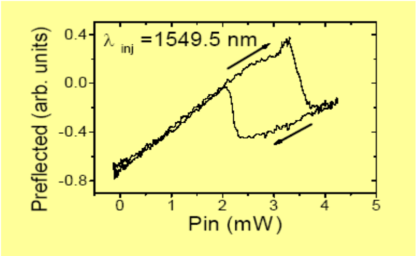
Large optical nonlinearities through injection of carriers

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

dispersive nonlinearity

optical switching, bistability

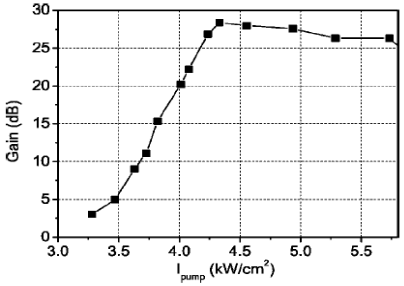




F. Raineri et al, Opt. Lett. 30, 64 (2005)

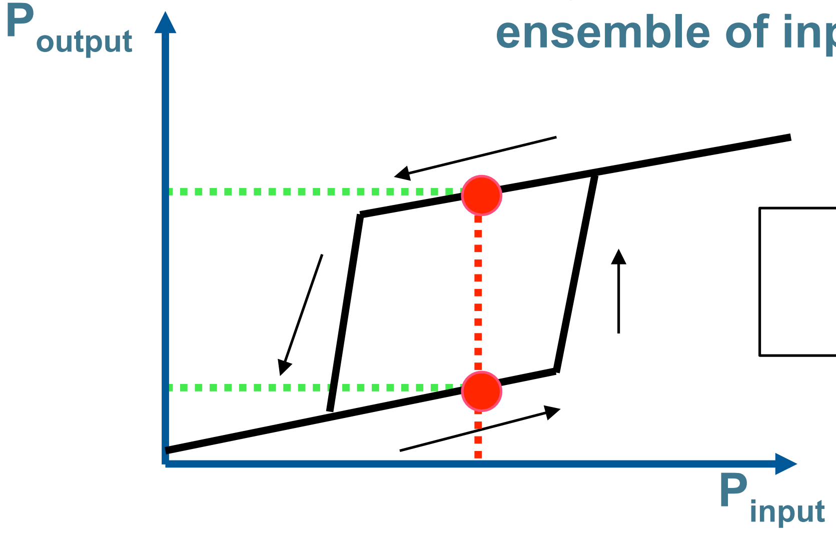
absorption/gain nonlinearity

amplification, laser emission, bistability



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

Optical Bistability through injection locking



Bistability = 2 possible paths for the same ensemble of input parameters

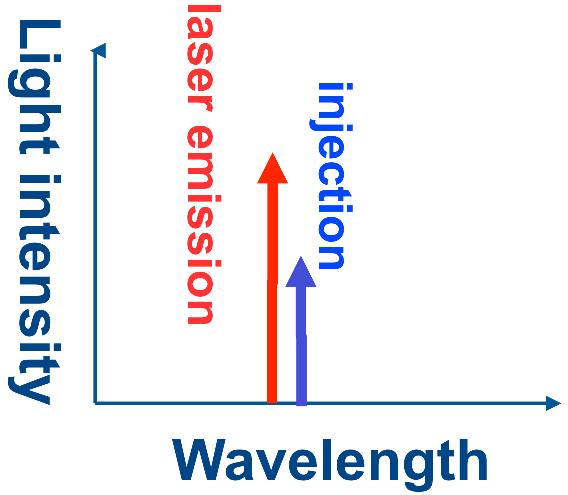
Important applications: data processing, logic functions,transistor , memory

How is it achieved?

→ Resonator+nonlinear material (dispersive nonlinearity or absorption/gain saturation)

Optical Bistability of injected PhC laser

What if we inject a red-shifted (λ_{inj}) external laser in free running laser state (λ_0) ?



→ carrier density changes through stimulated emission

Optical Bistability of injected PhC laser

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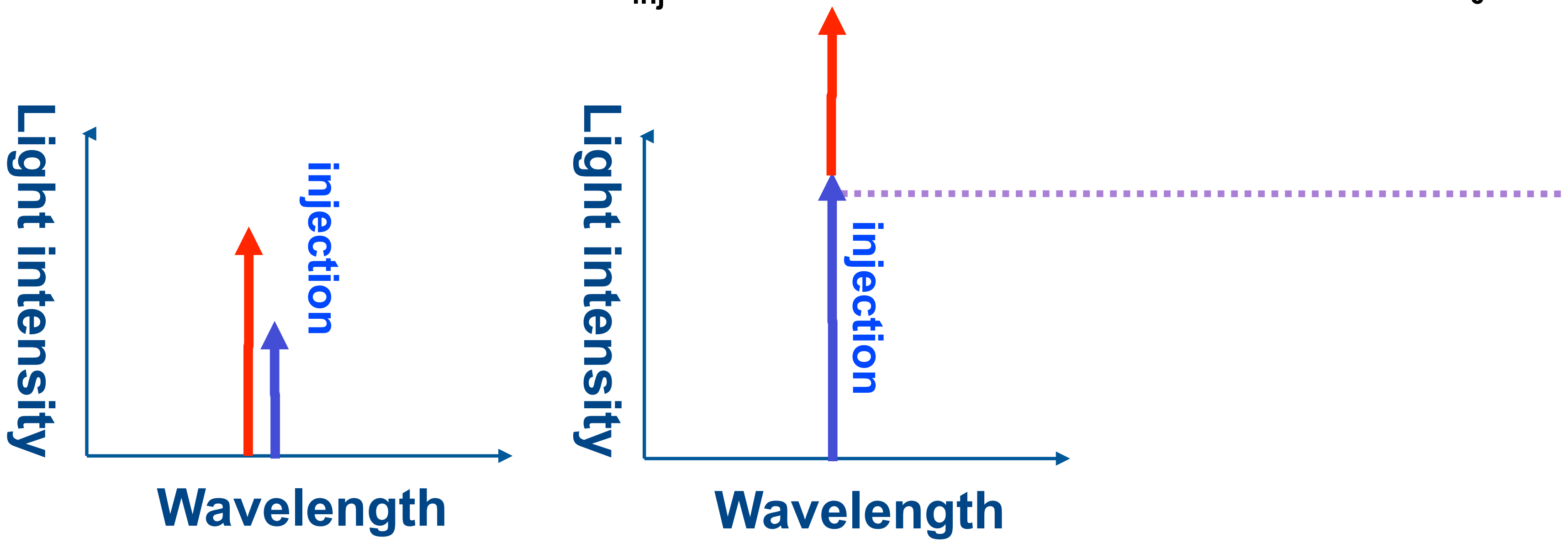

→ carrier density changes through stimulated emission

→ as injected power is increased, laser is locked at λ_{inj}

→ $\lambda_0=\lambda_{inj}$ and injected intracavity intensity is higher

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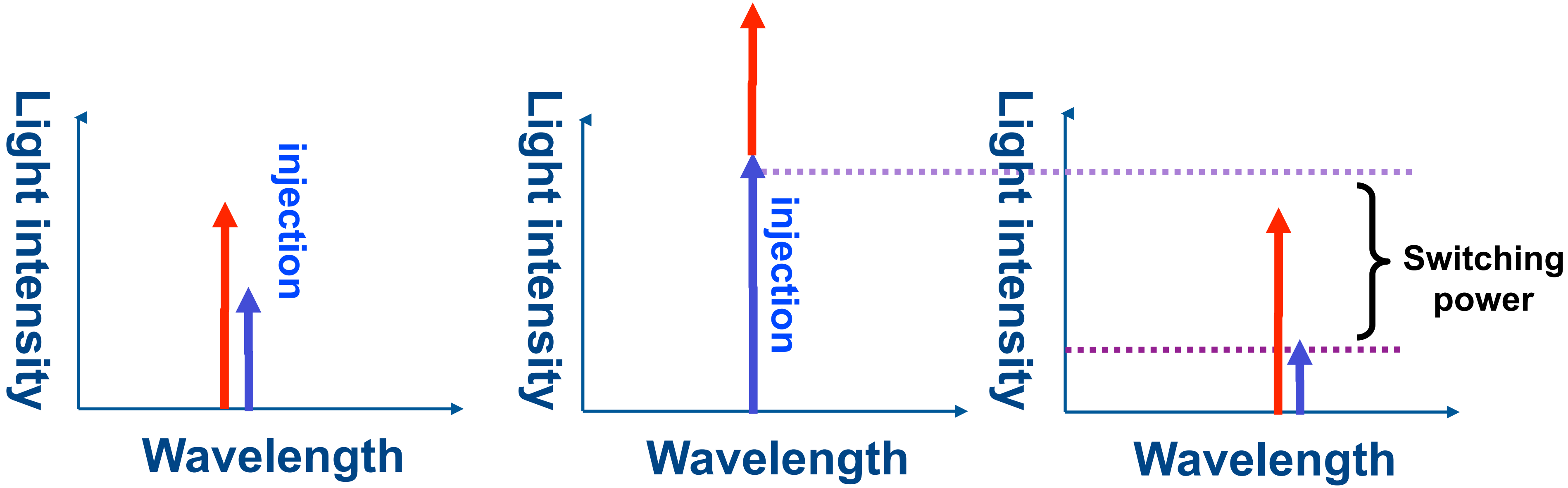

→ carrier density changes through stimulated emission

→ as injected power is increased, laser is <u>locked</u> at λ_{inj}

→ $\lambda_0=\lambda_{inj}$ and injected intracavity intensity is higher

→ from locked state, injected power has to be decreased to a lower level than the initial level in order to recover the unlocked regime

Optical Bistability of injected PhC laser

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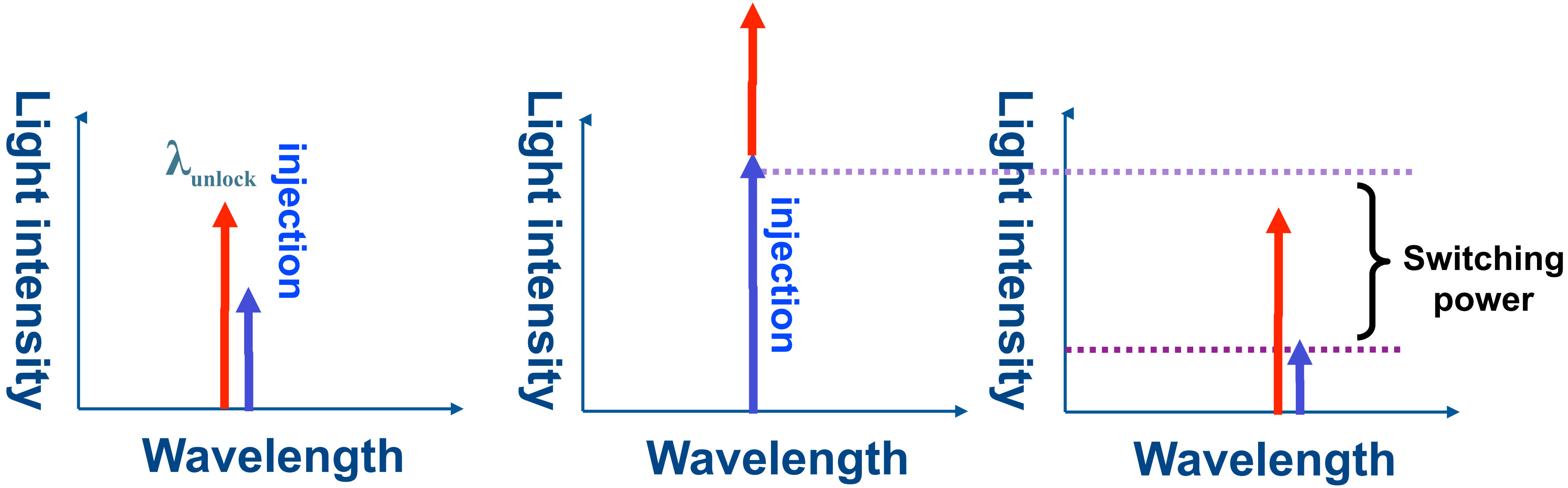


→ carrier density changes through stimulated emission

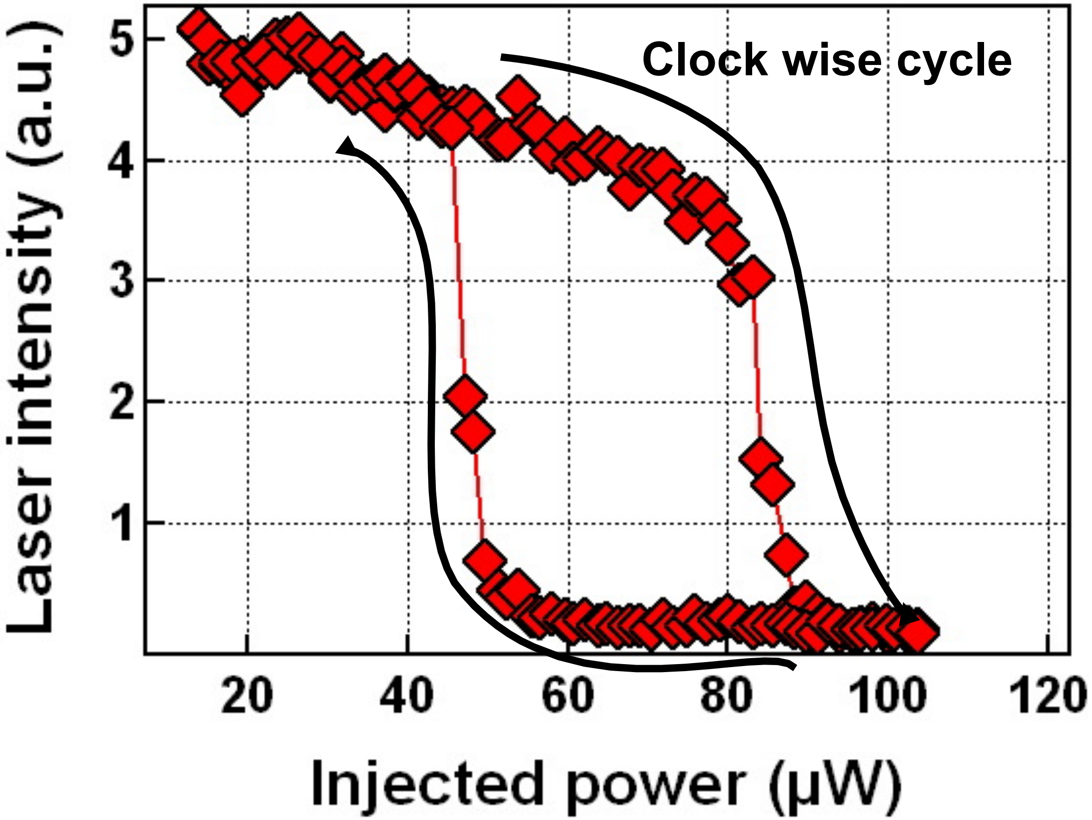
→ as injected power is increased, laser is locked at λ_{inj}

→ $\lambda_0 = \lambda_{inj}$ and injected intracavity intensity is higher

→ from locked state, injected power has to be decreased to a lower level than the initial level in order to recover the unlocked regime

→ emitted power at λ_{unlock} versus injected power will present an hysteresis cycle

Hysteresis cycle



→ bistable threshold = 50µW

→ high contrast (>20dB)

→ switching power < 40 µW

→ switching energy < 0.4 fJ for 10ps pulses!

Dynamics determined by laser dynamics → measured to be faster than 50ps

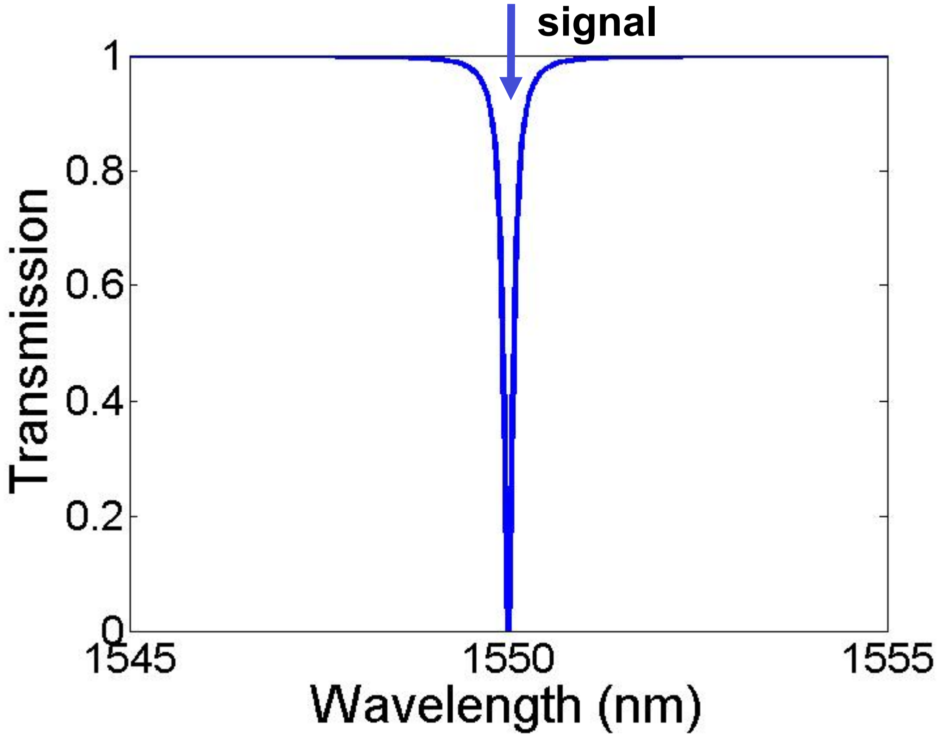
PROWOC

ULTRAFAST SWITCHING

Ultrafast all-optical switching

Principle

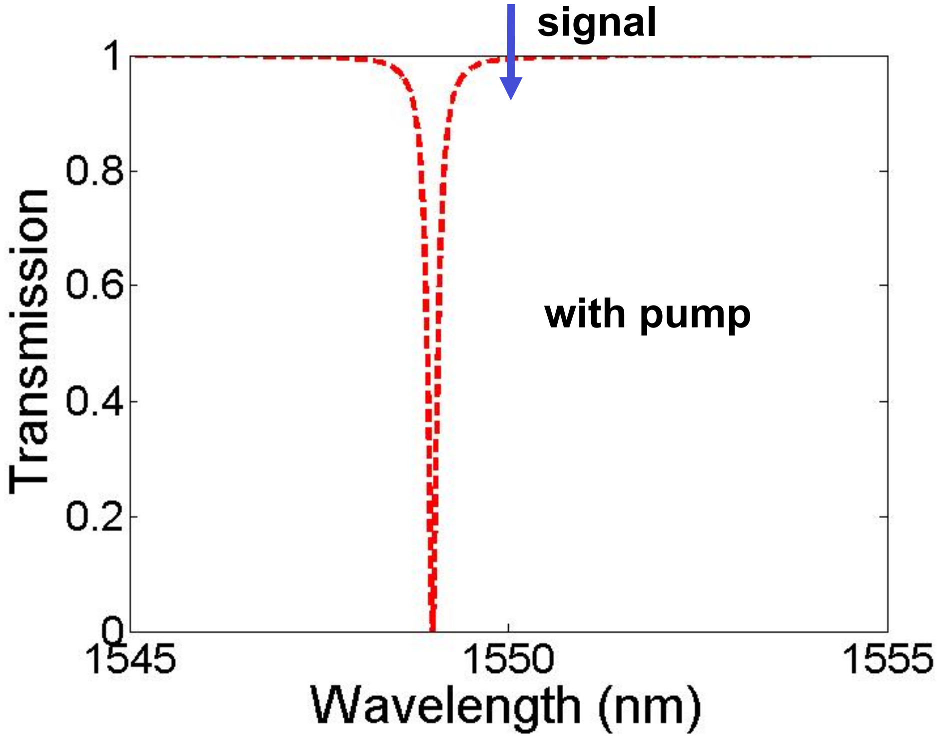
Change of refractive index through optical carrier injection



Ultrafast all-optical switching

Principle

Change of refractive index through optical carrier injection

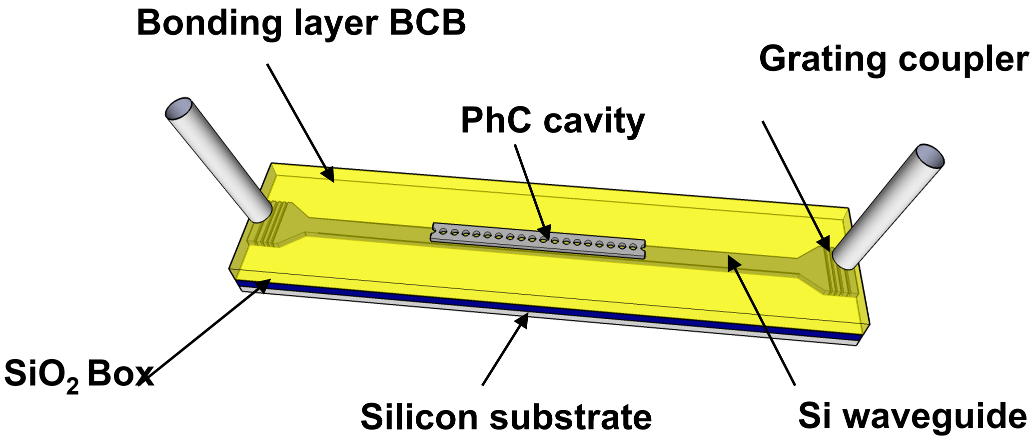


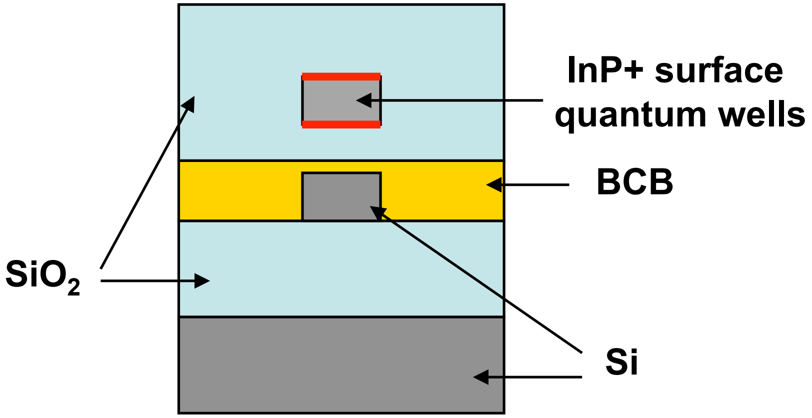
Dynamics determined by carrier lifetime

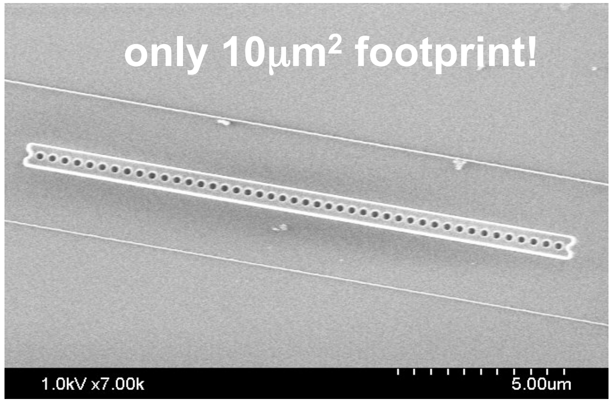
→Reduction of carrier lifetime by enhancing surface recombination

Ultrafast switching

Reduction of carrier lifetime using surface InGaAs QW and material patterning





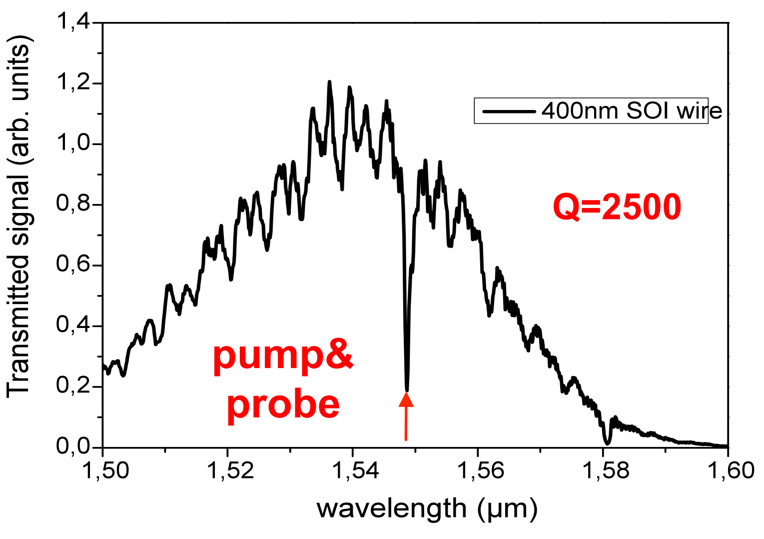


Fully embedded in SiO_2 for robustness and increased heat sinking

Ultrafast switching

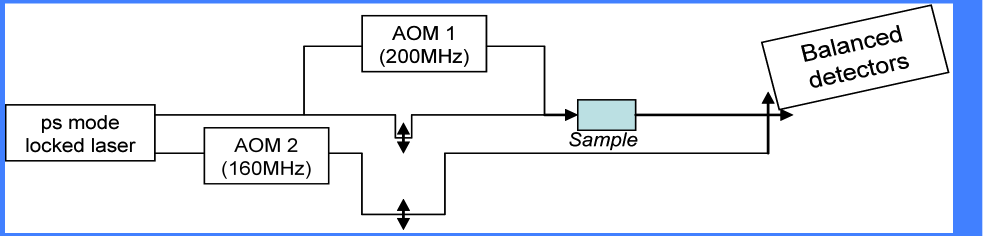
Measurements

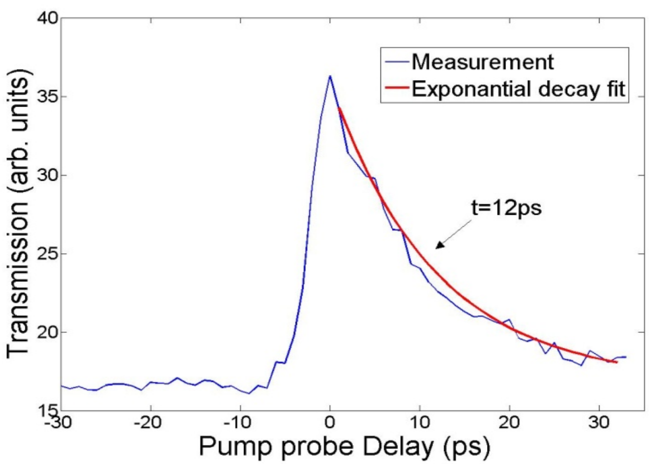
Transmission characterisation



→ induced blue shift of the resonant by the pump

Quasi degenerate pump-probe experiment with balanced heterodyne detection



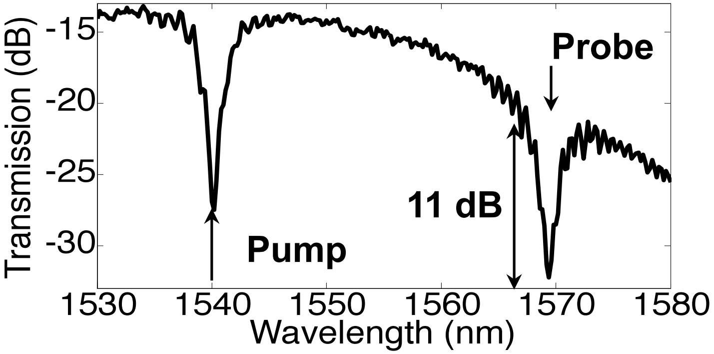


→ 12ps carrier lifetime!

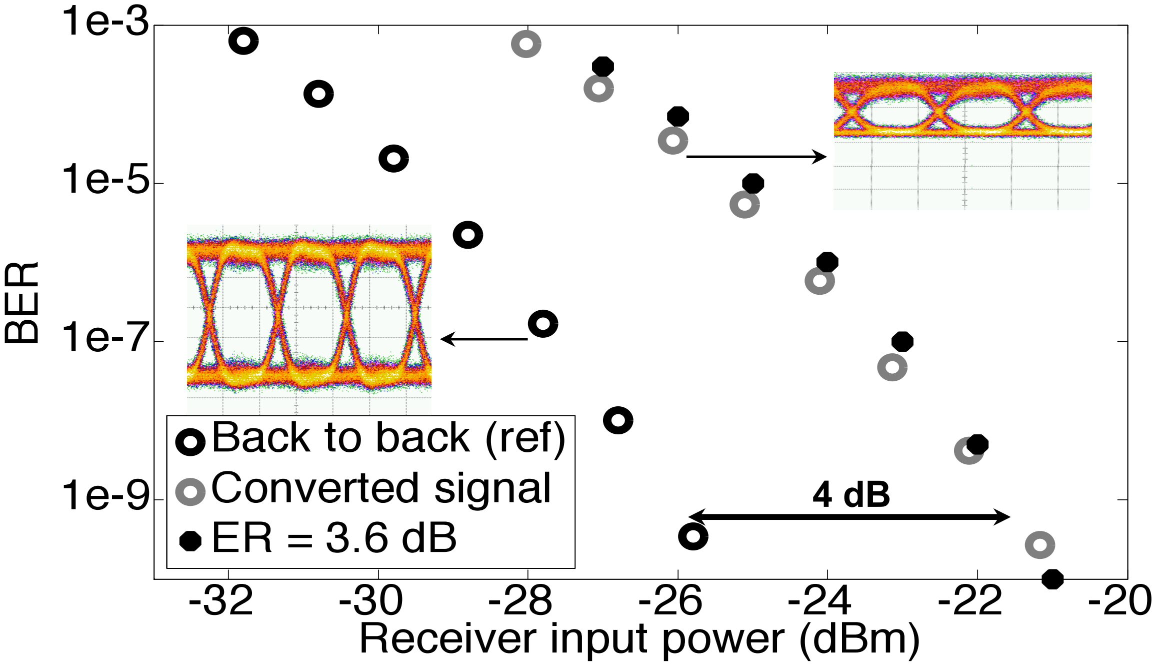
→ Switching energy of 40fJ!

10Gbits/s Wavelength conversion

Measured @ Foton CNRS UMR 6082 **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!

cnrs dépasser les frontières

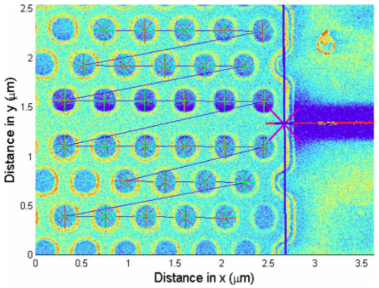
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

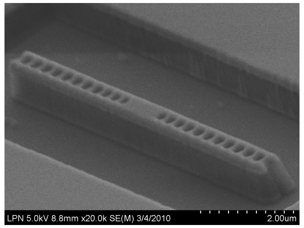
Conclusion

Hybrid goes nano!

→ nanoscale structure

→ alignment better than 30 nm



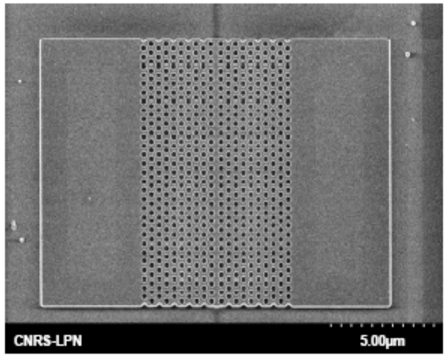


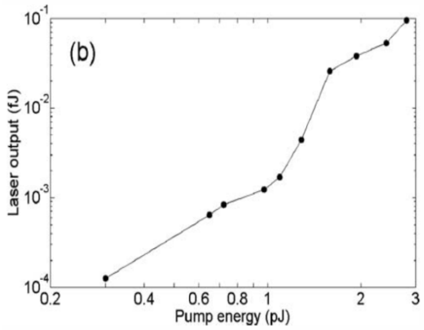
T. J. Karle et al, J. Appl. Phys. 107 063103 (2010)

Demonstration of integrated PhC laser

→ Slow light

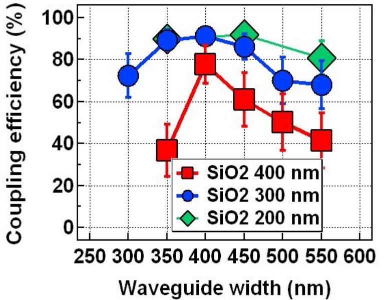
→ Cavity





Y. Halioua et al,
Appl. Phys. Lett. 95 201119 (2009)

Good extraction achieved !



→ separation layer dependent

→ phase-matching dependent

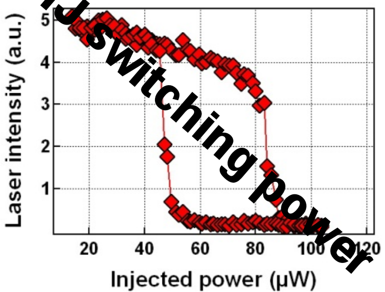
Coupling efficiency > 90%

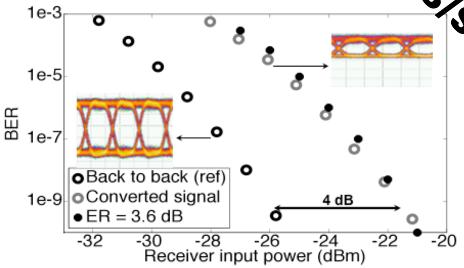
Y. Halioua et al, Opt. Express 19, 9221 (2011)

Bistable switch in laser and ultrafast switching

sub fJ switching power

10Gbits/s

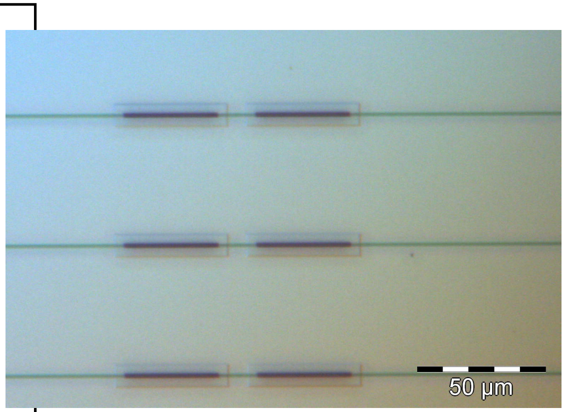




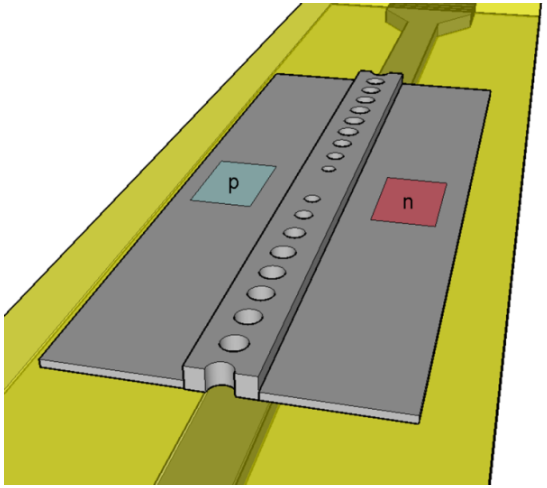
Future work

Cascaded blocks

- Multi functional
- Coupled Resonators and associated effects



Electrical pumping:



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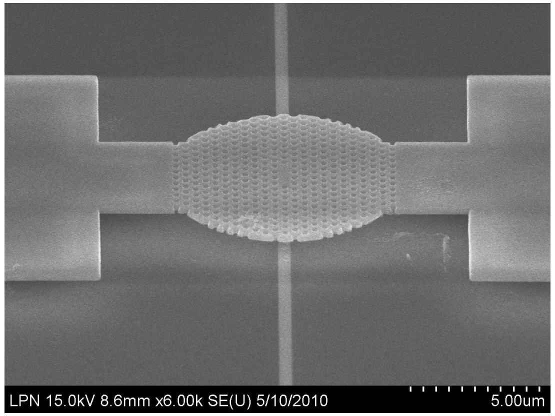
S. Matsuo et al, Opt. Express 20(2012).

Optomechanics:



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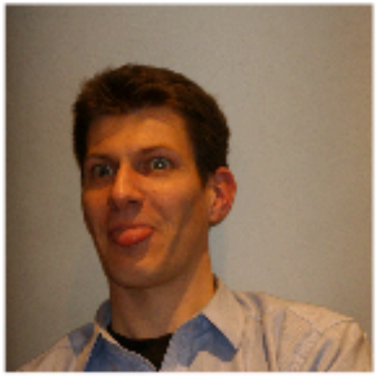
The actors

Alexandre Bazin

Yacine Halioua

Rémy Braive

Tim Karle



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