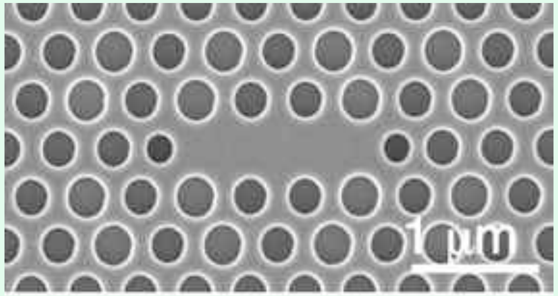
Integrated Nanophotonics: Issues and opportunities

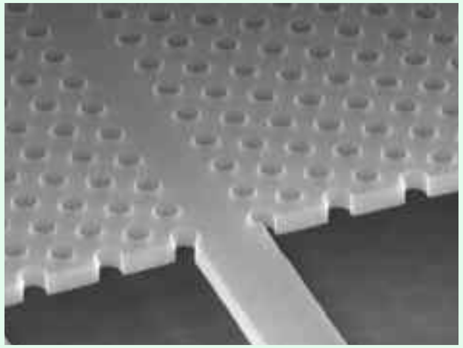
Thomas F Krauss

University of St. Andrews, SUPA, School of Physics and Astronomy,
St Andrews, UK

Key collaborators: Pavia & Catania, Italy



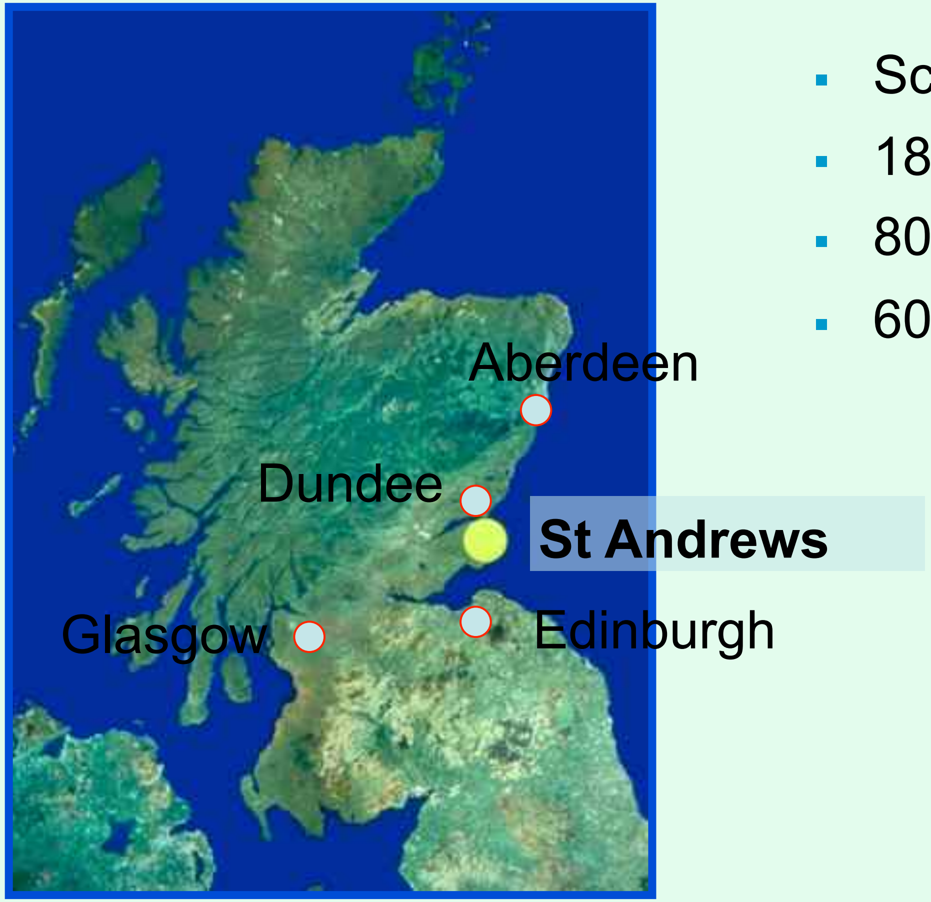
Lecsin



St Andrews
Scotland’s First University

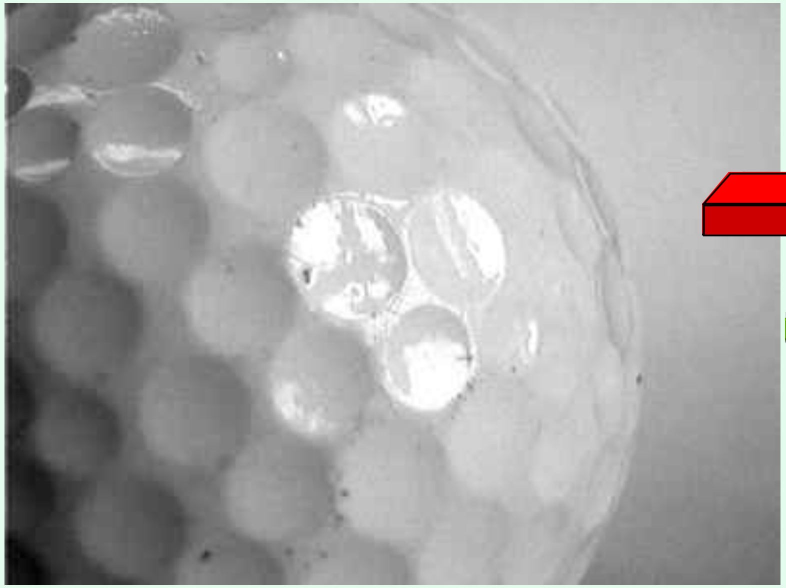
Thomas F Krauss

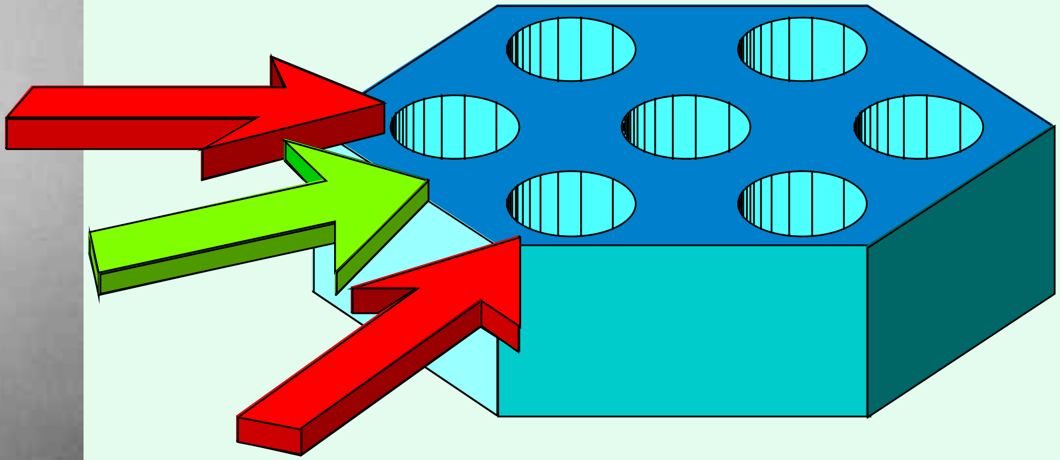
University of St Andrews



- Scotland, UK
- 18,000 people (1/3 students)
- 80km from Edinburgh
- 600 km from London

St Andrews. The home of golf

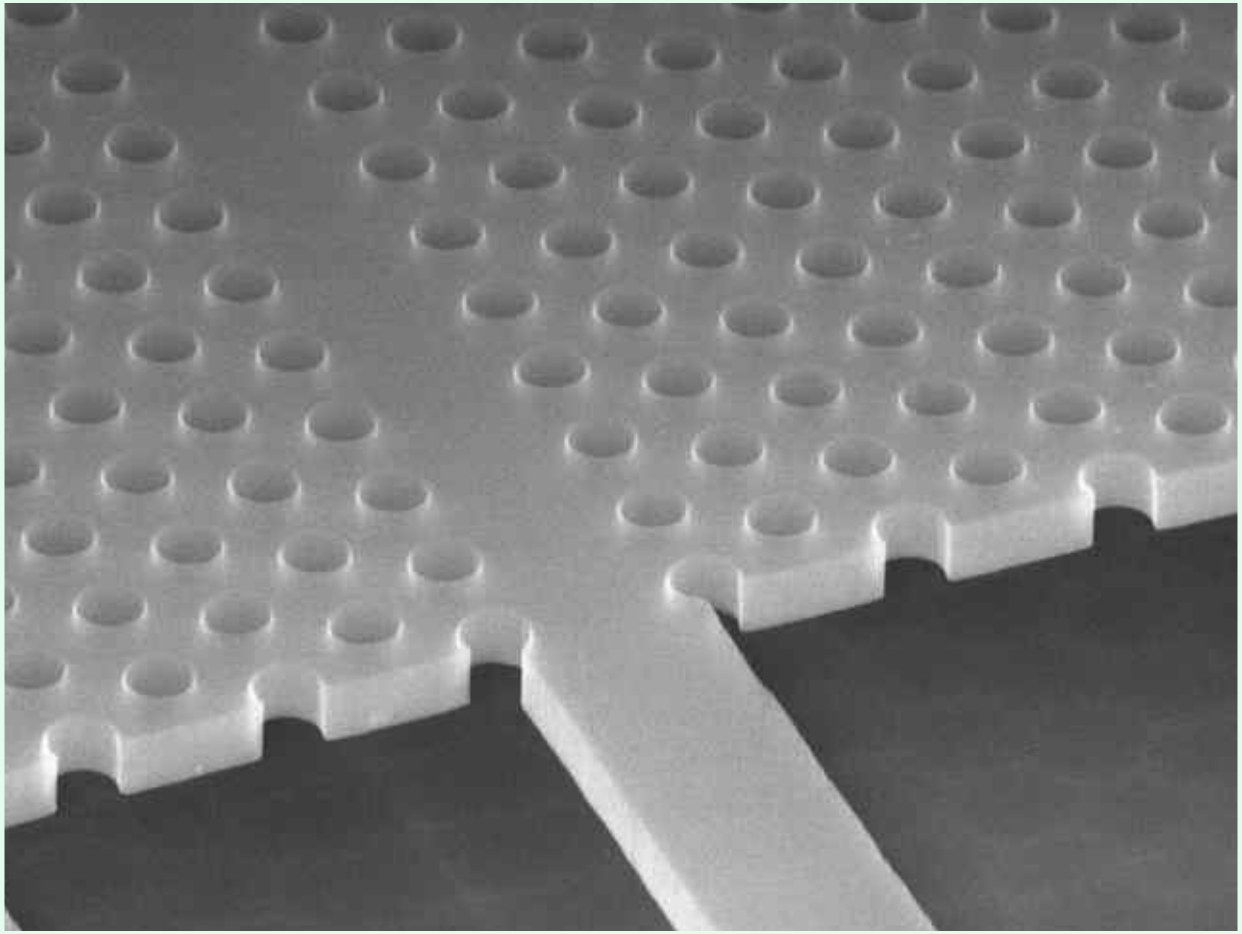




LEO 1530 SEM/ Raith Elphy Plus

CAIBE machine

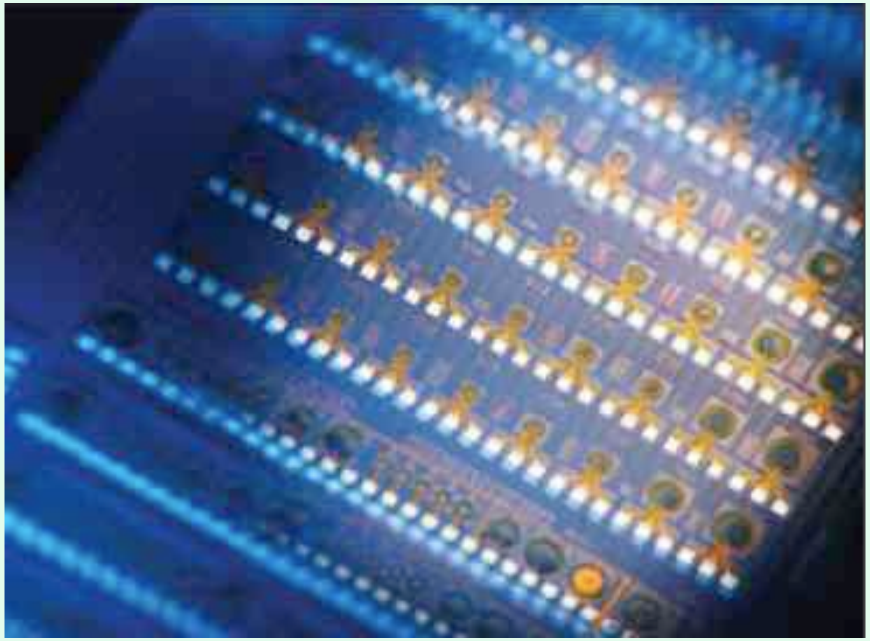
Photonic crystal waveguides



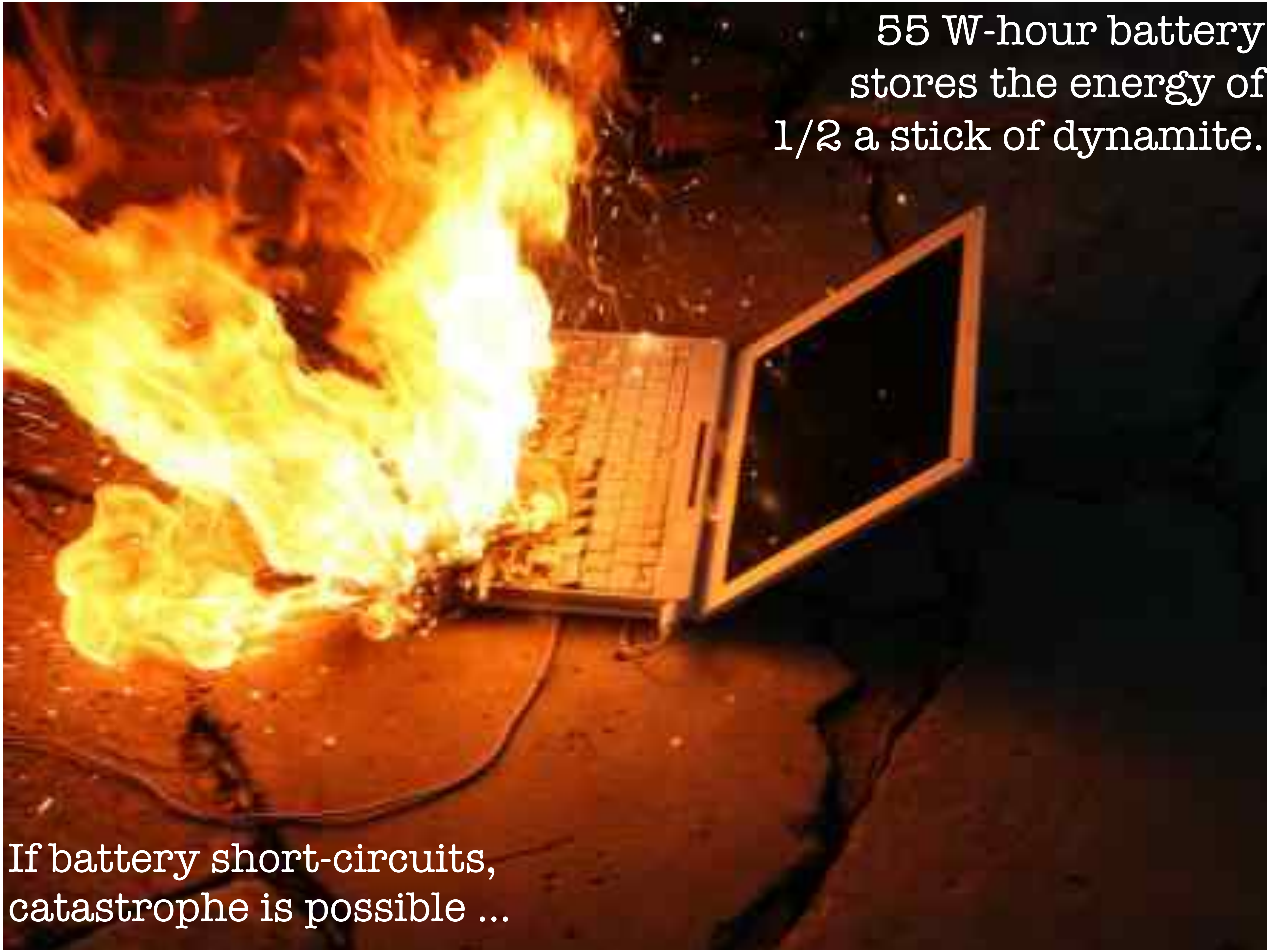
220 nm Si waveguide, airbridge or oxide clad

epixnet nanostructuring platform: www.nanophotonics.eu

Silicon Photonics



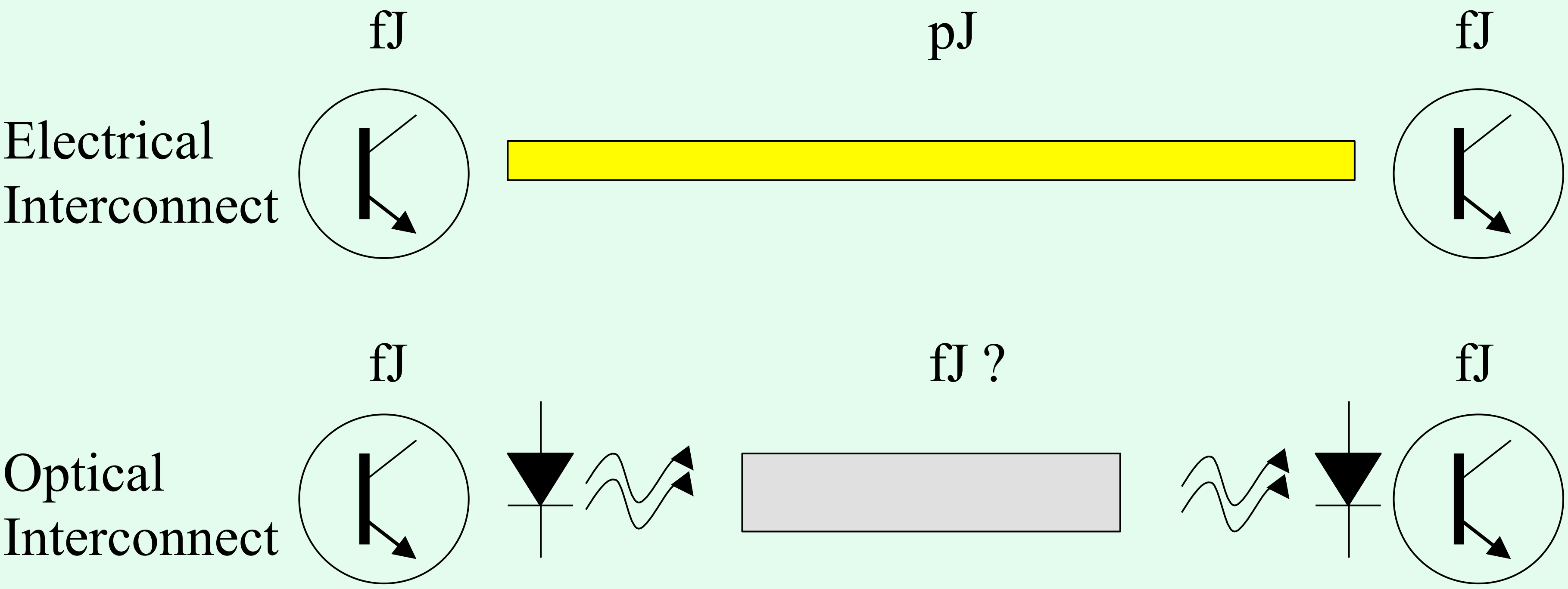
What’s the problem silicon photonics is trying to solve ?



55 W-hour battery
stores the energy of
1/2 a stick of dynamite.

If battery short-circuits,
catastrophe is possible ...

Optical interconnects save energy



fJ

pJ

fJ

Electrical Interconnect

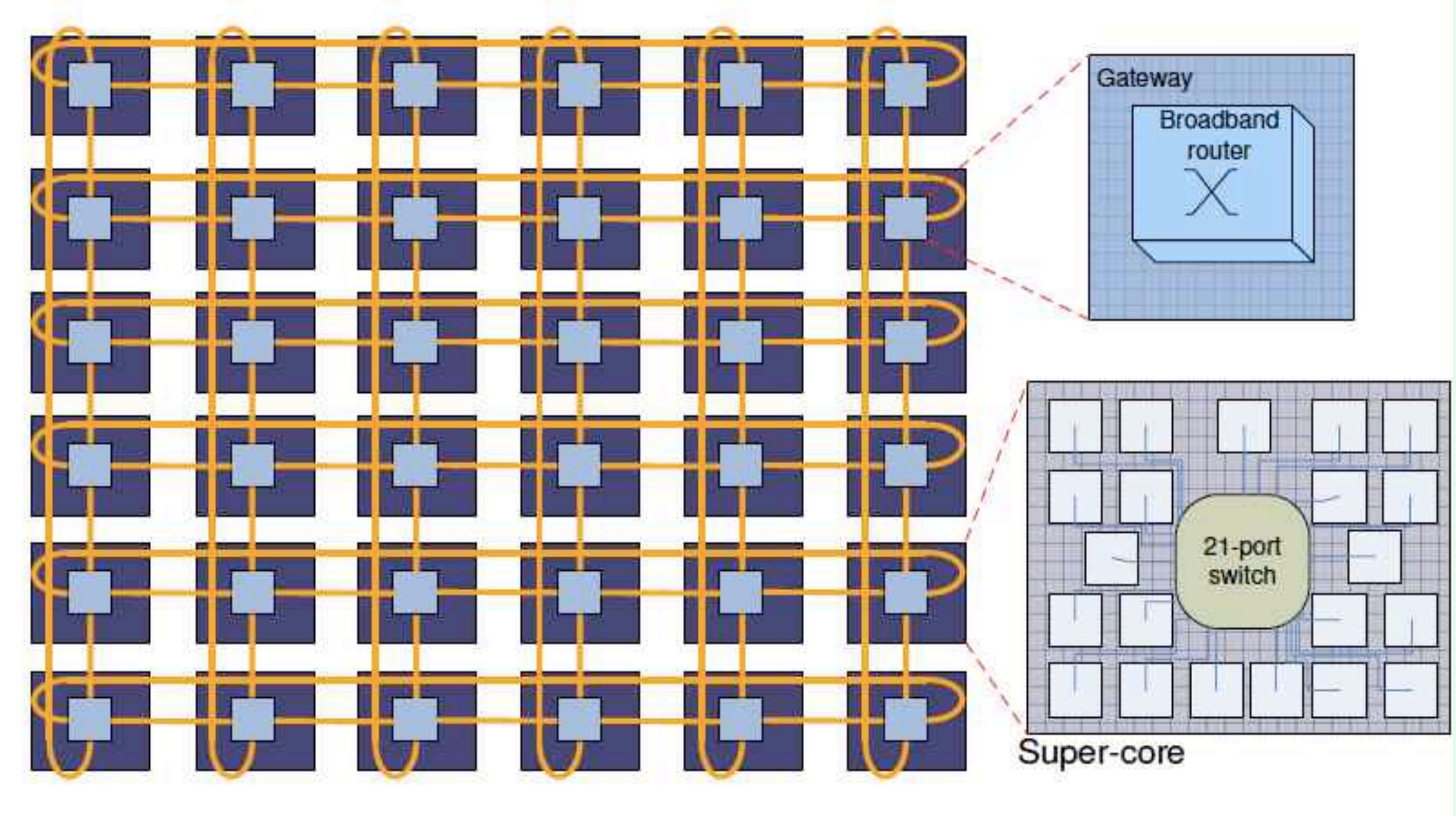
fJ

fJ ?

fJ

Optical Interconnect

On-chip Optical Interconnects



Use the photonics layer to shift data in a multicore architecture

Peter Kogge, DARPA study on Exascale Computing

Possible monolithic realisation

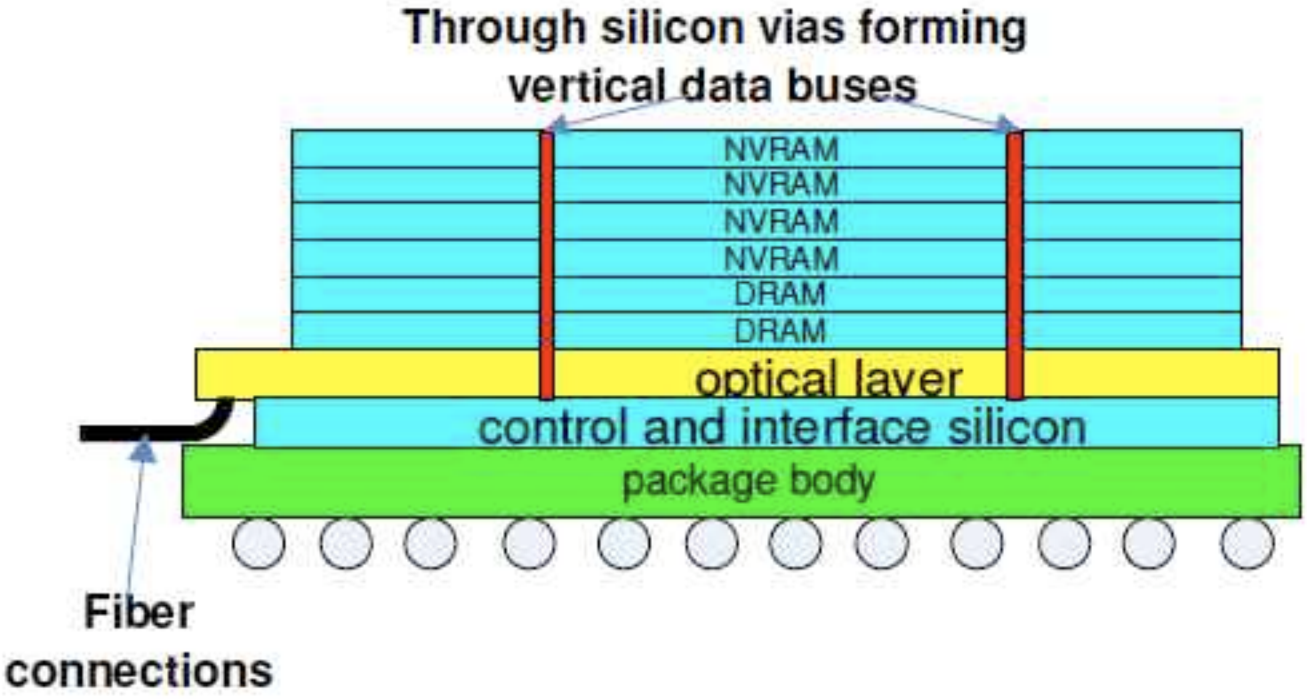


Figure 7.25: A possible optically connected memory stack.

Peter Kogge, DARPA study on Exascale Computing

Optical Interconnect: 1.1 TB/s HUB; 1,000,000 links

- 192 GB/s Host Connection
- 336 GB/s to 7 other local nodes in the same drawer
- 240 GB/s to local-remote nodes in the same supernode (4 drawers)
- 320 GB/s to remote nodes
- 40 GB/s to general purpose I/O

Avago microPOD™

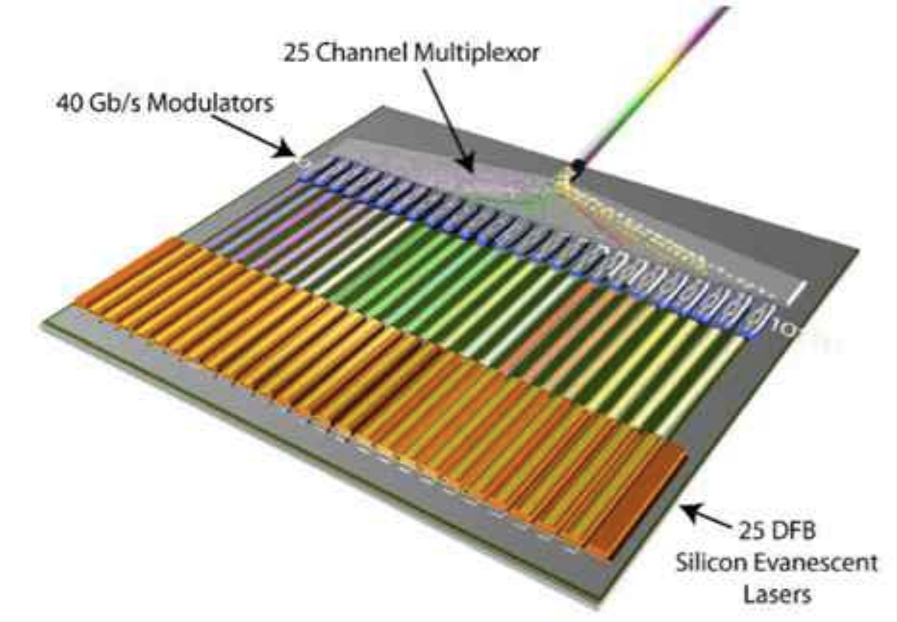
[M. Fields, Avago, OFC 2010, paper OTuP1]

[A. Benner, IBM, OFC 2010, paper OTuH1]

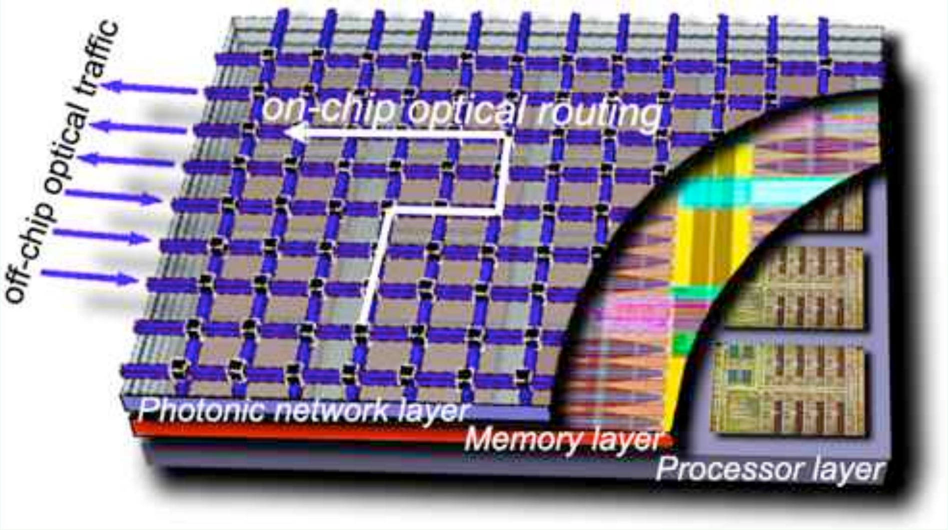
http://www.ncsa.illinois.edu/BlueWaters/

Optical interconnects

INTEL

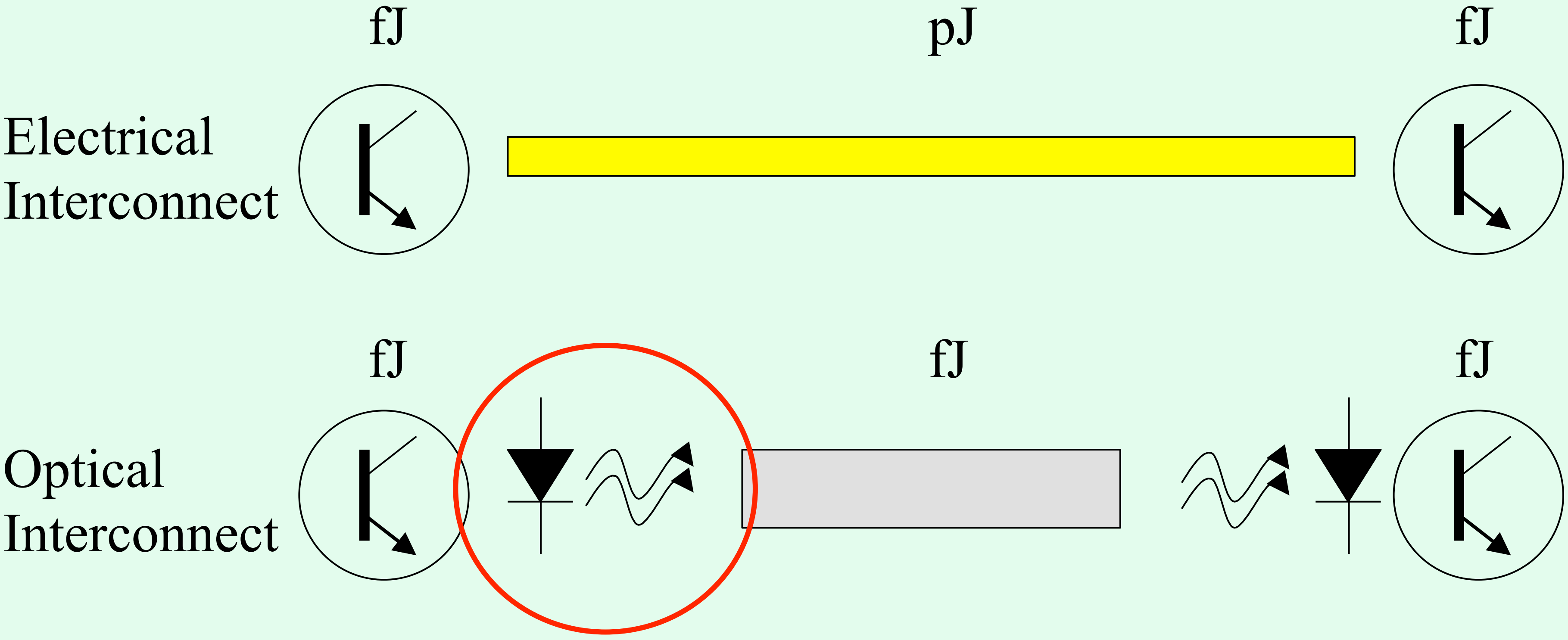


IBM



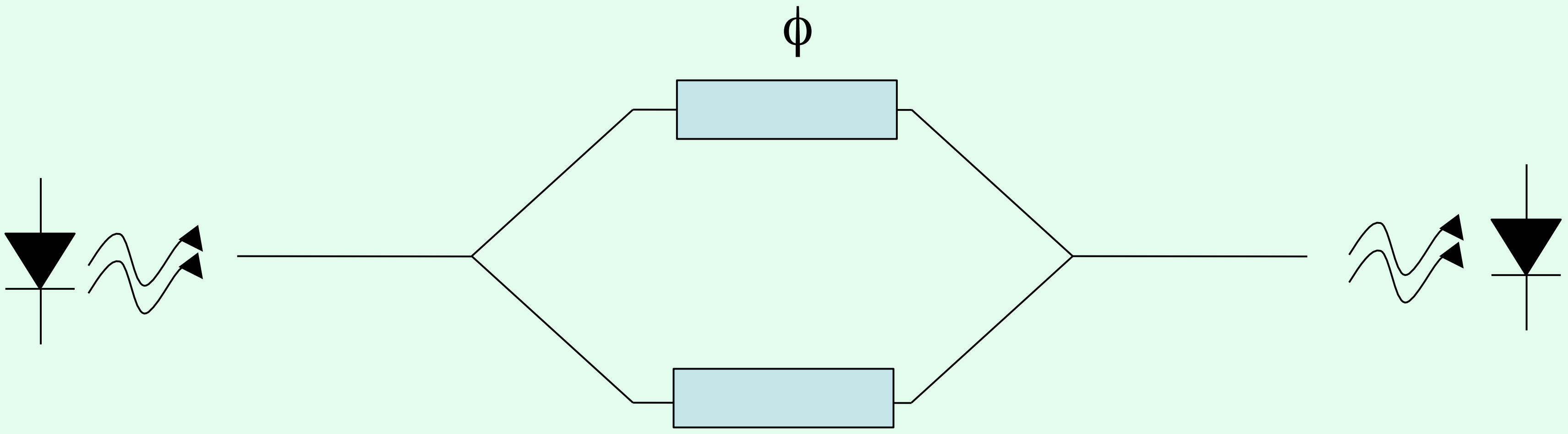
The idea is to use optical signals to distribute information on-chip, between processors.

Optical interconnects save energy



External lightsource + modulator

External Lightsource + Modulator



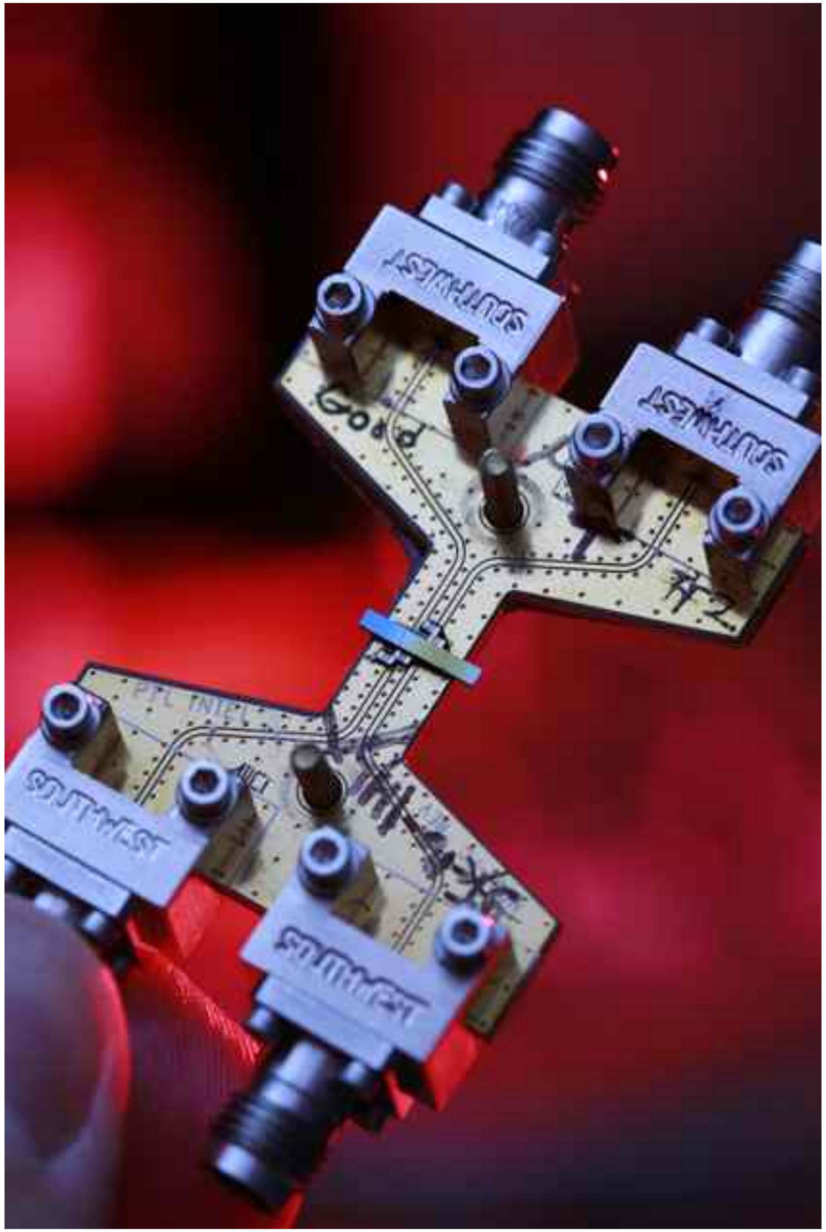
Requirements: Fast (ideally ps) => Carrier modulation

=>Typical Δn≈10^{-4}

=>Typical length ≈ cm

$$\Delta\Phi = \pi$$

$$k_0 \Delta n L = \pi \quad \Rightarrow \quad L = \frac{\lambda}{2\Delta n} \quad \approx \quad 10^4 \lambda$$

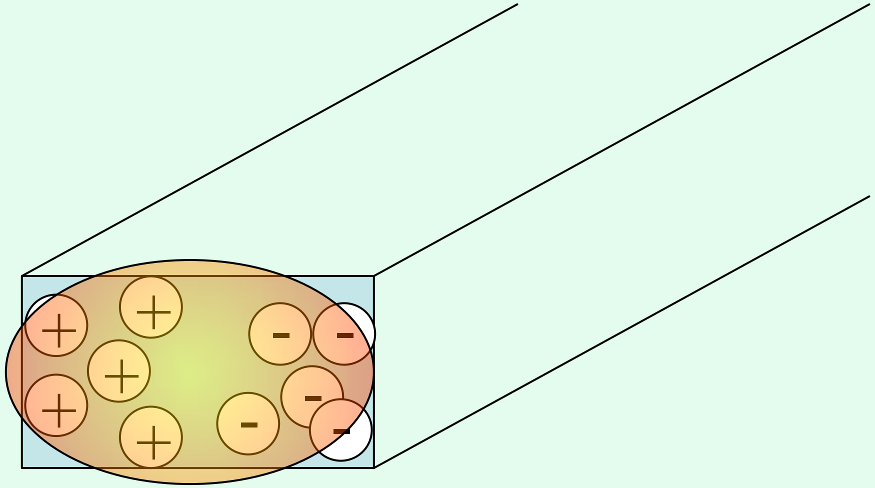


Intel

Solution: Resonant enhancement.

Effective optical path maintained.

Electrical path reduced.

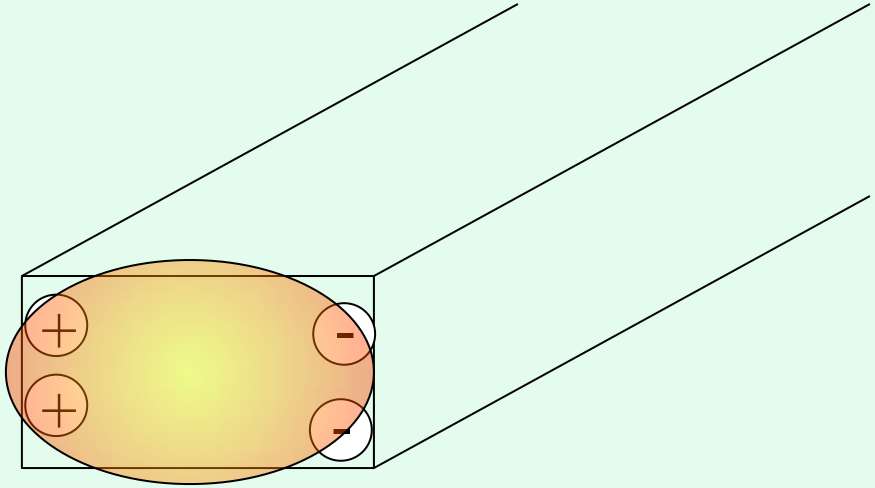


Volume of active carriers reduced.

Solution: Resonant enhancement.

Effective optical path maintained.

Electrical path reduced.



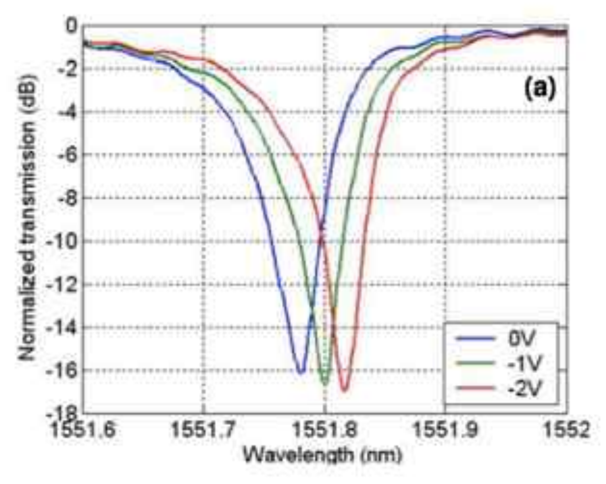
Volume of active carriers reduced

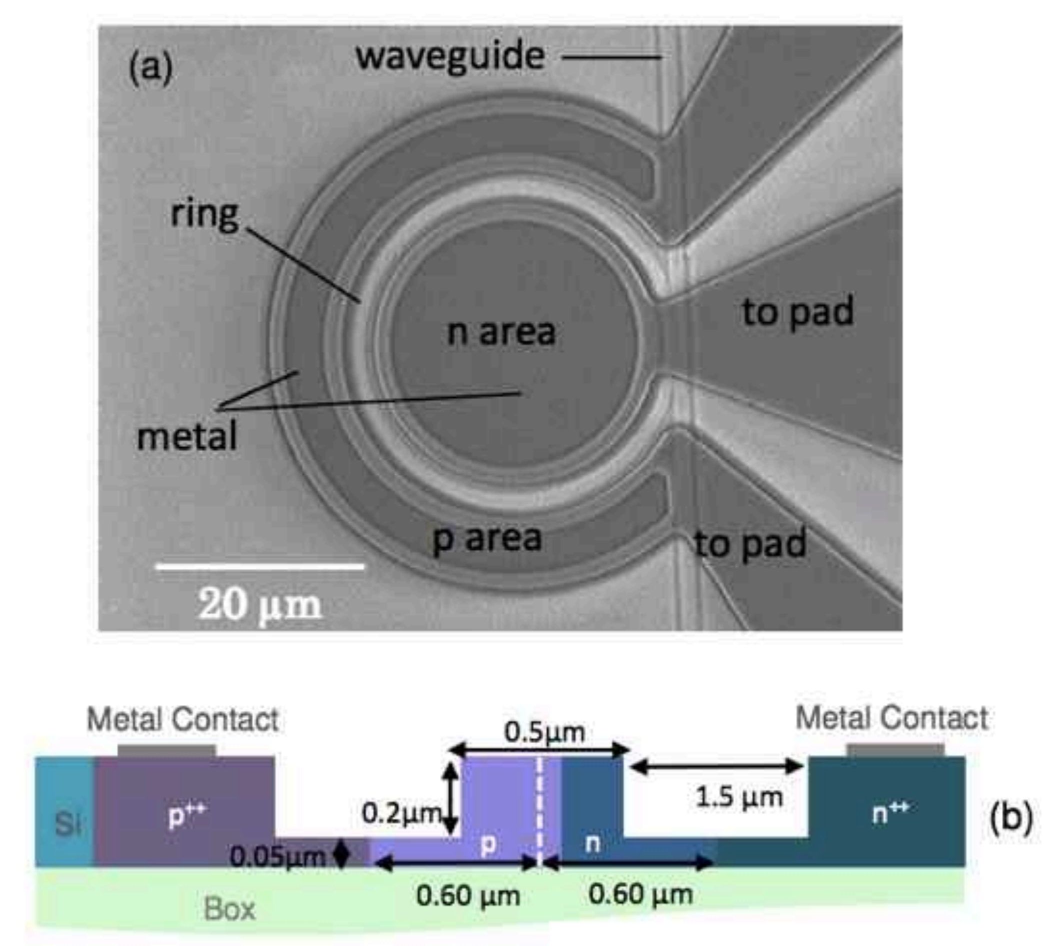
State-of-the-Art

Kotura ring:

30µm dia. = 100µm circumf.
50 fJ/bit
10 GHz bandwidth

Tuning energy: > 100 fJ/bit
Tolerances ?





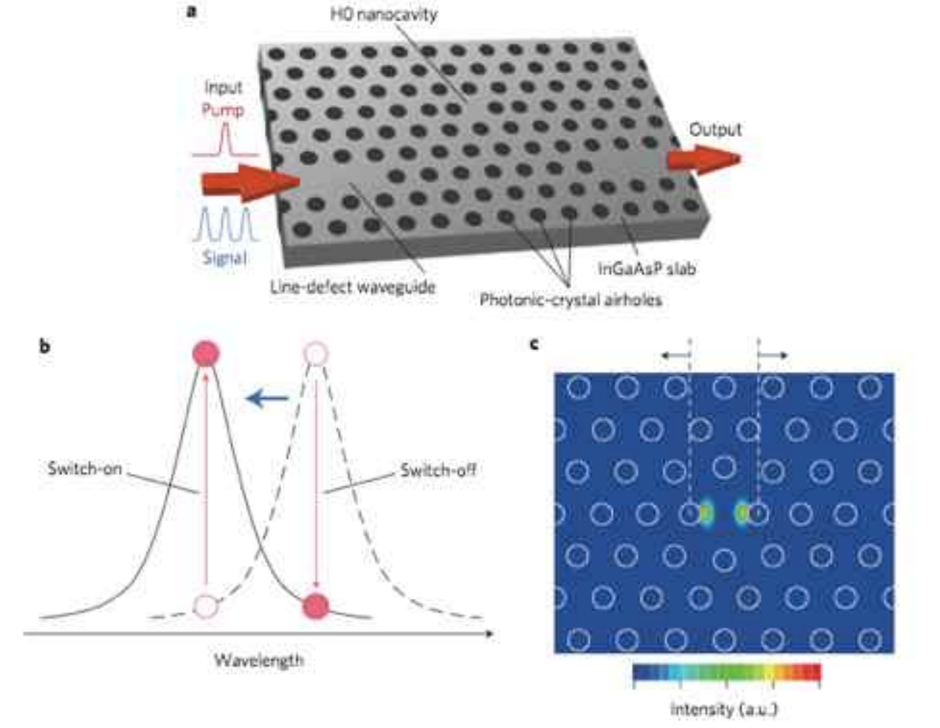
OpEx 17, 22484 (2009)

nature photonics

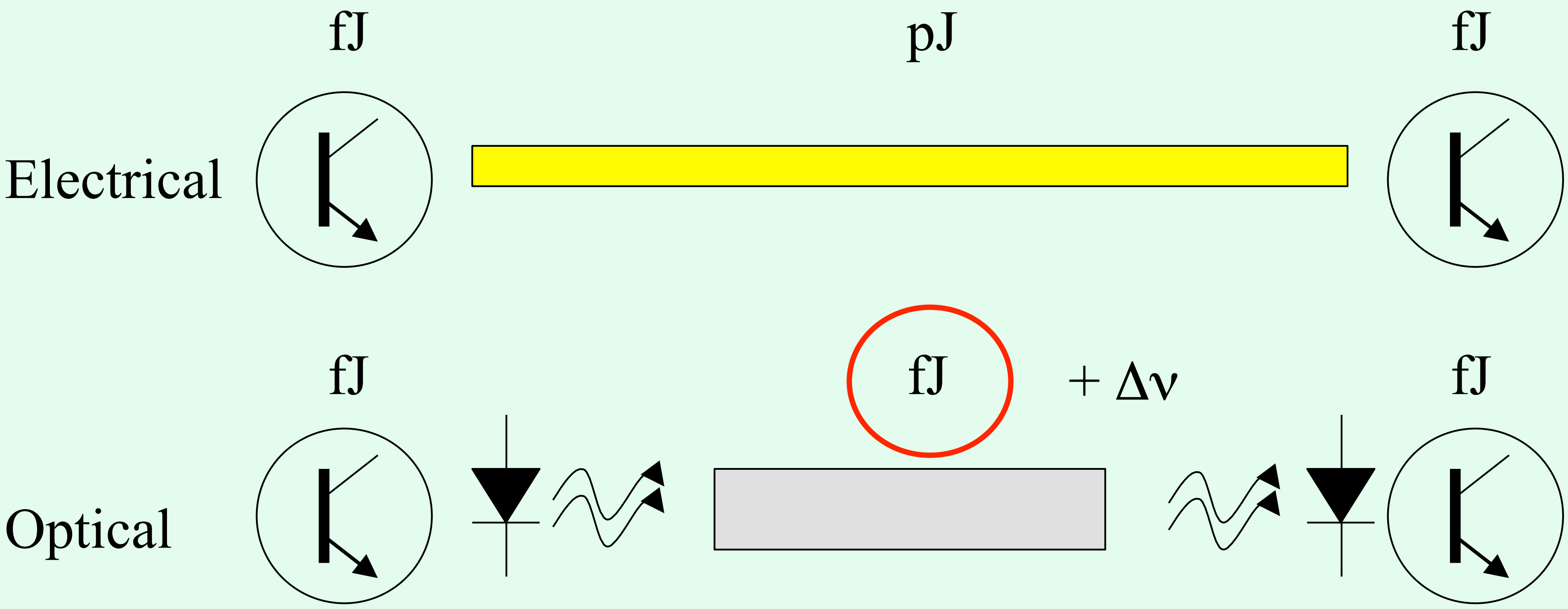
ARTICLES

Sub-femtojoule all-optical switching using a photonic-crystal nanocavity

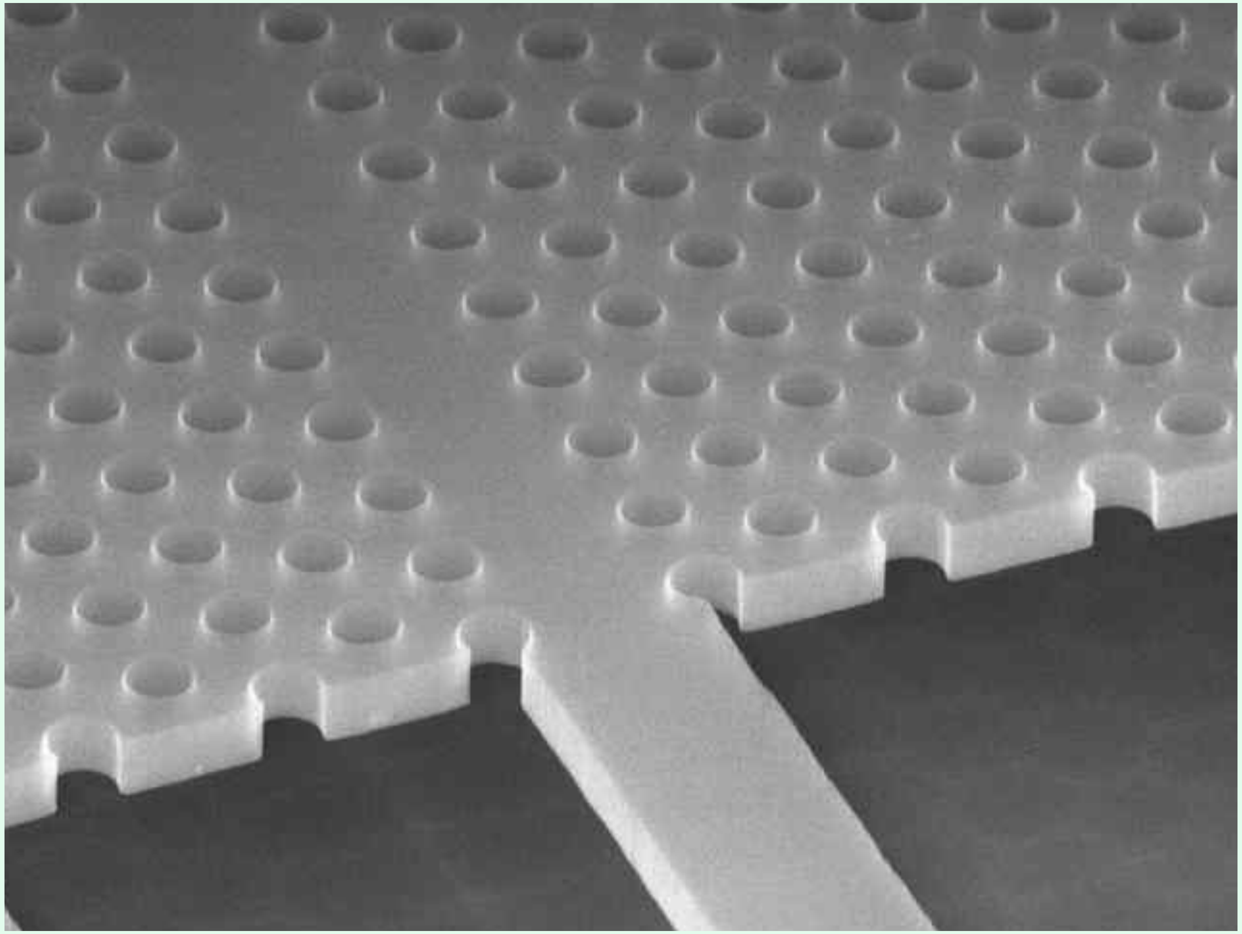
Kengo Nozaki[1]*, Takasumi Tanabe[1,2], Akihiko Shinya[1,2], Shinji Matsuo[3], Tomonari Sato[3], Hideaki Taniyama[1,2] and Masaya Notomi[1,2]*



Optical interconnects save energy

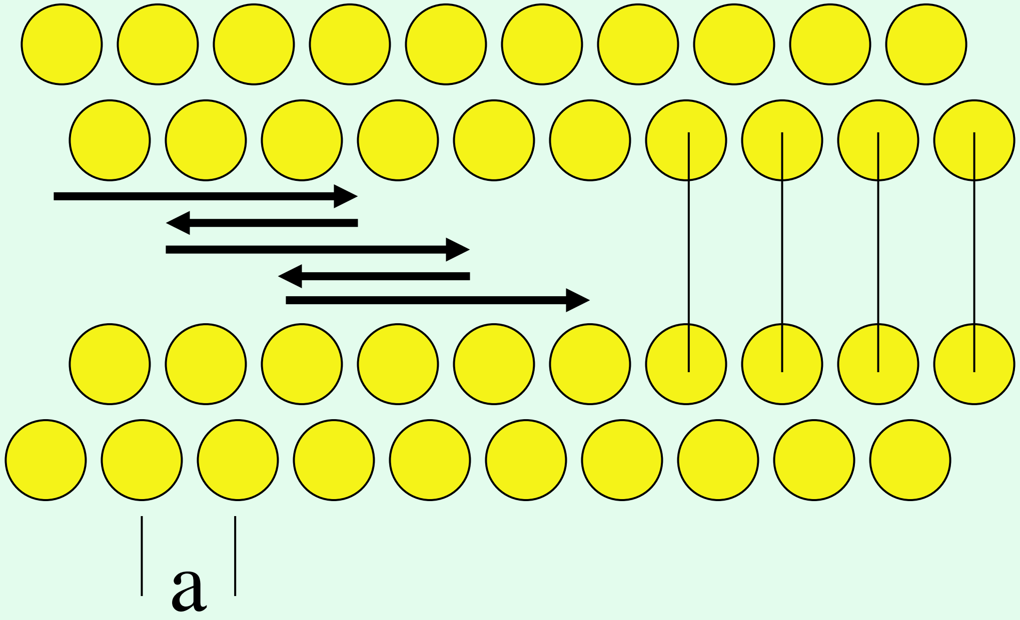


Photonic crystal waveguides



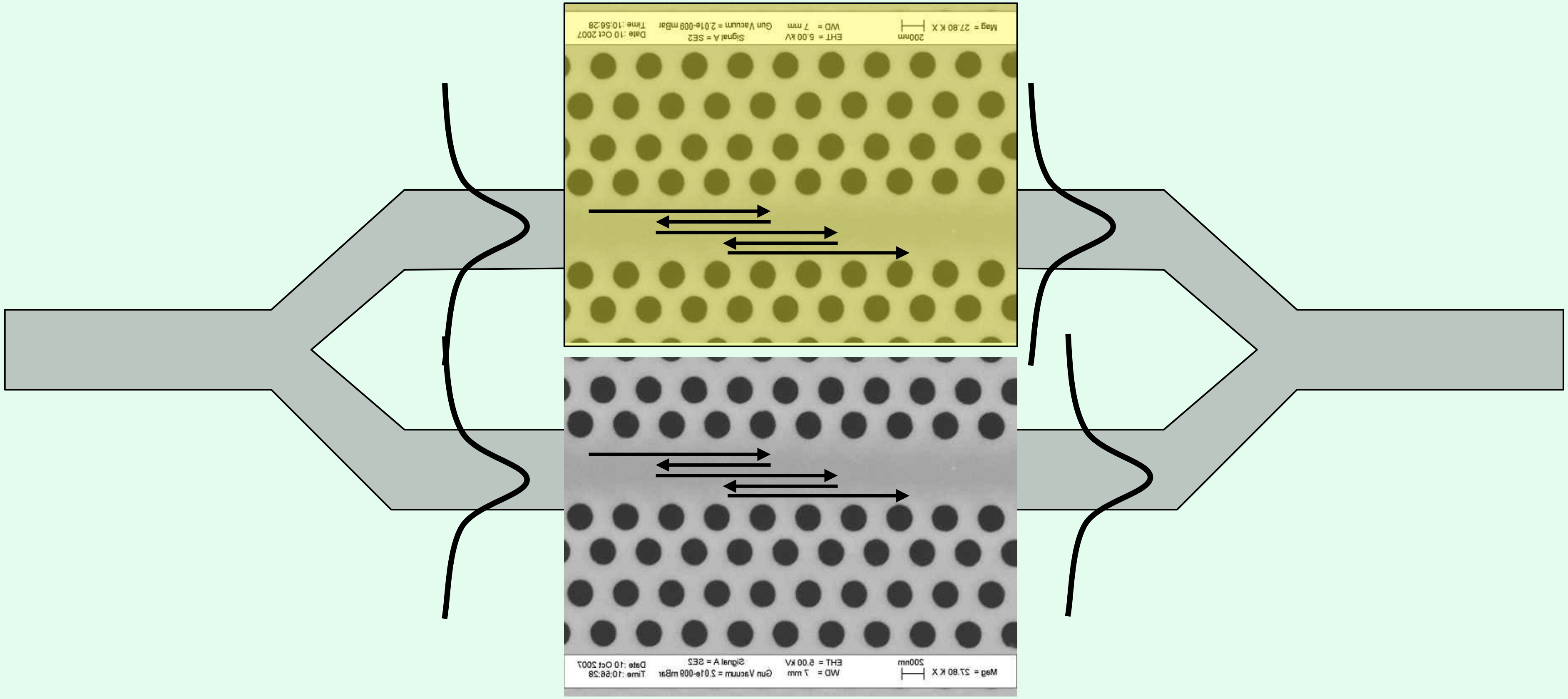
220 nm Si waveguide, airbridge or oxide clad

Slow Light Mechanism



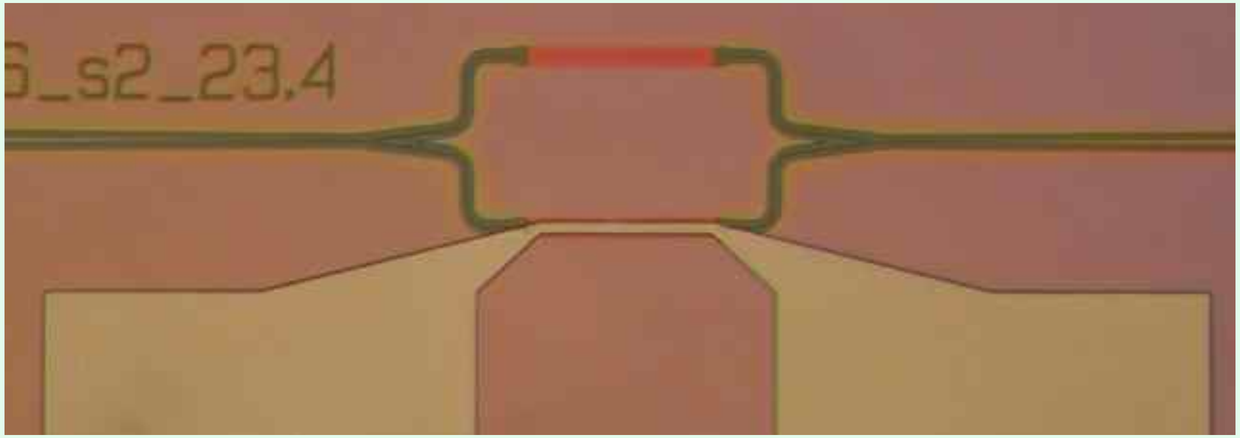
In the slow light regime, one can imagine the mode taking a longer route - that's why it takes more time, and why there is more light inside the structure.

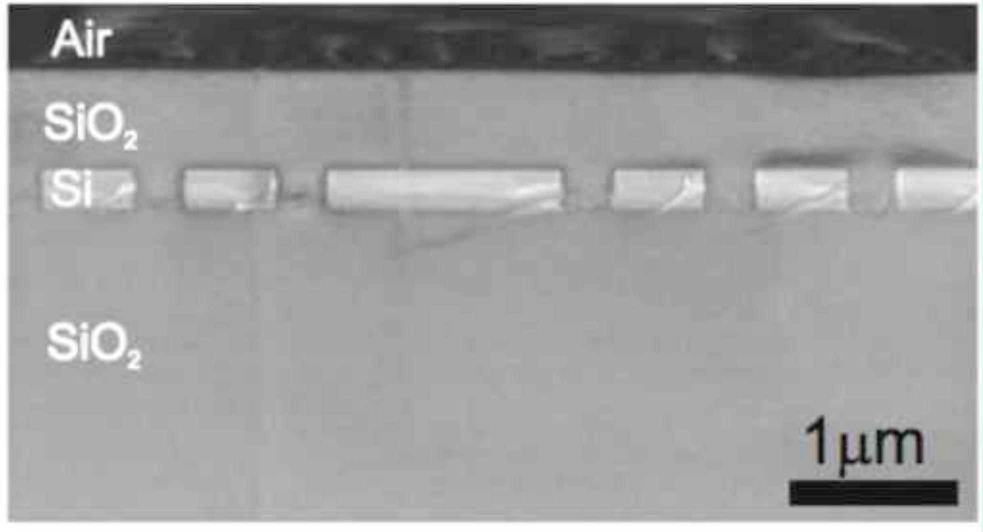
PhC MZI modulator



Thermally activated Mach-Zehnder

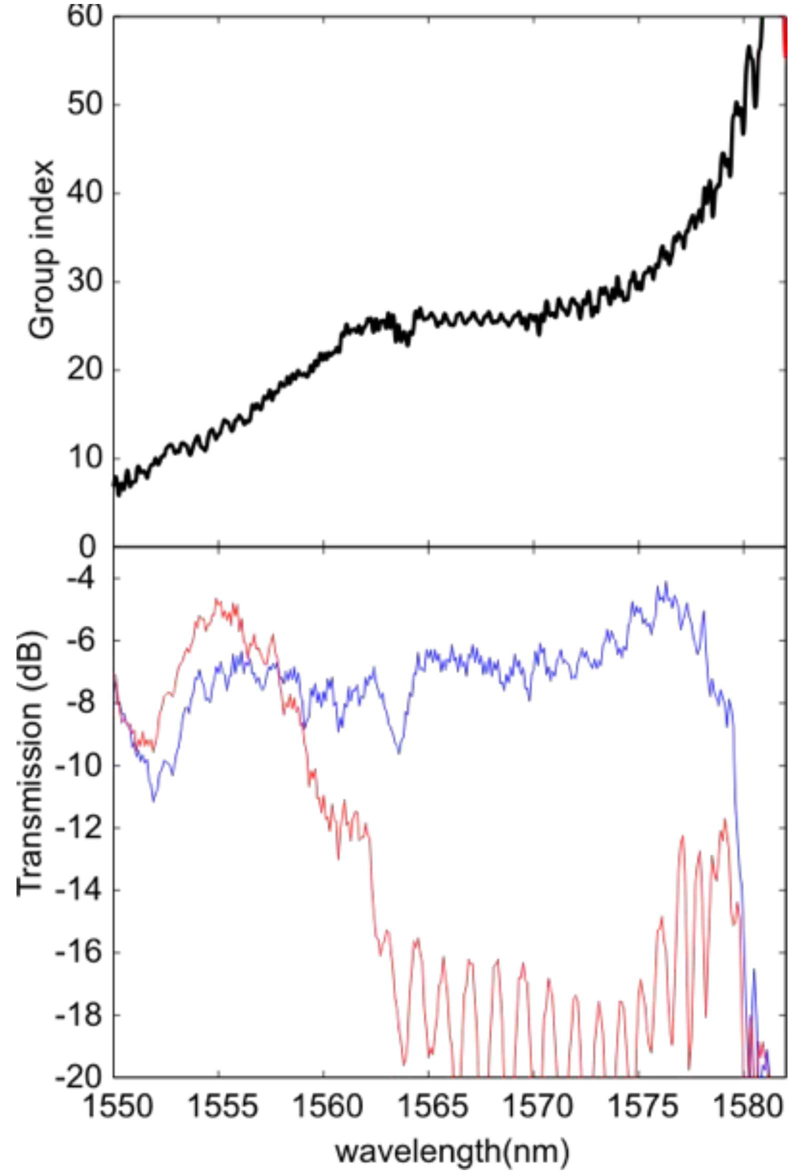
80 μm long PhC





L. O'Faolain et al., IEEE Photonics Journal 2, 404 (2010)

PhC – MZI Performance



Dispersion curve

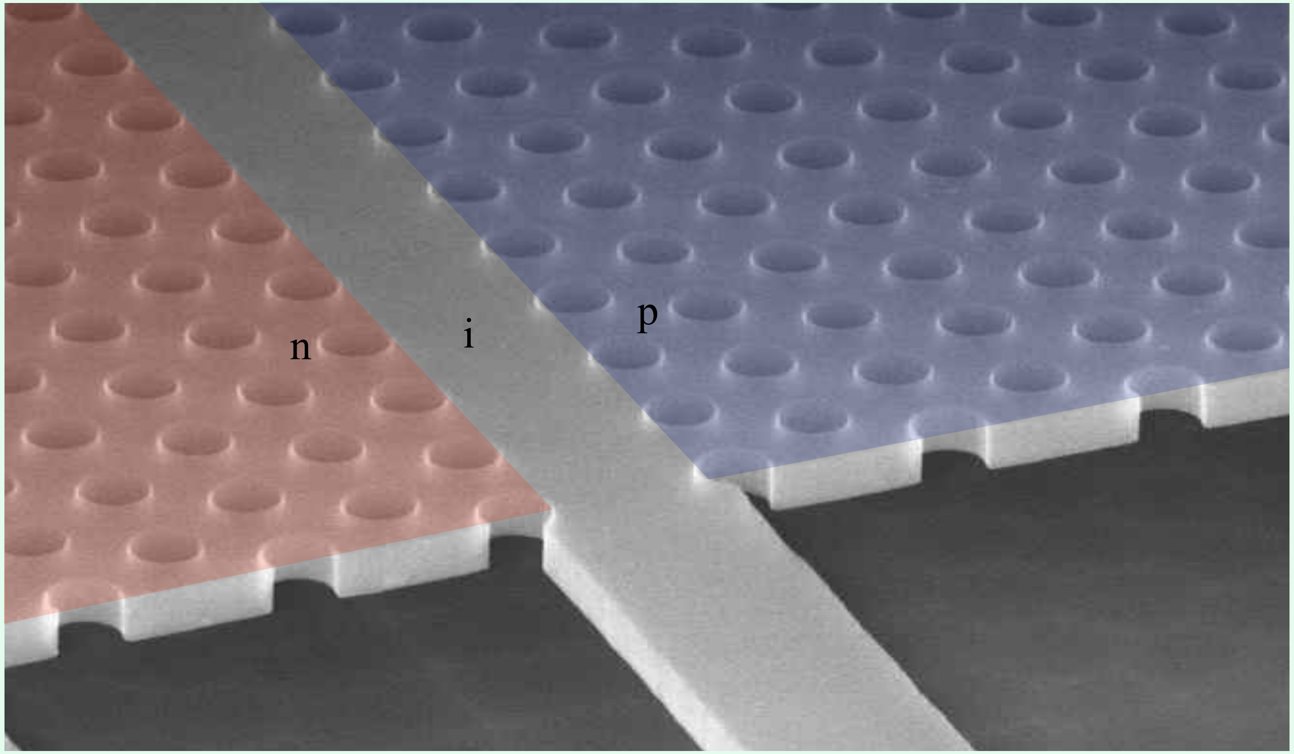
Switching performance

L. O'Faolain et al., IEEE Photonics Journal 2, 404 (2010)

Electrical operation

William Whelan-Curtin Kapil Debnath

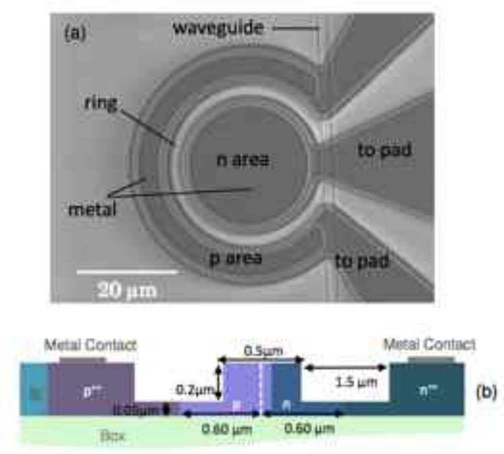
Electrical operation. Work in progress…..

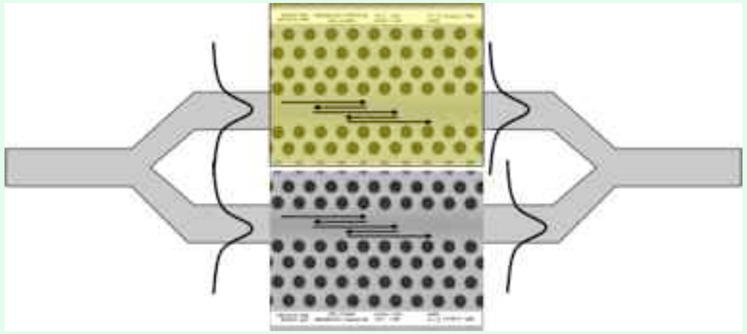


Conclusion modulator

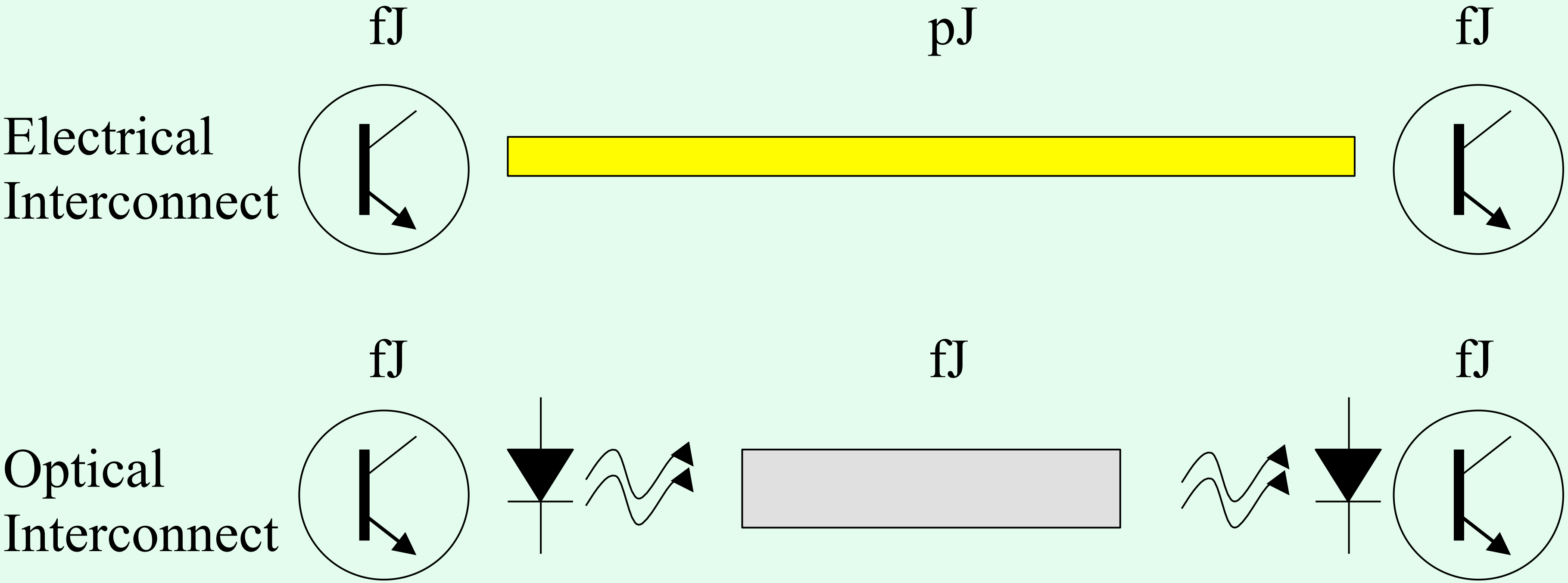
The slow light concept allows us to make small footprint, low driving power modulators with high bandwidth.

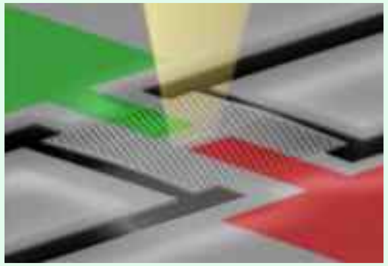
They are of similar size, and therefore capacitance, as State-of-the-Art microring resonators, but offer far more bandwidth and do not need to be tuned.



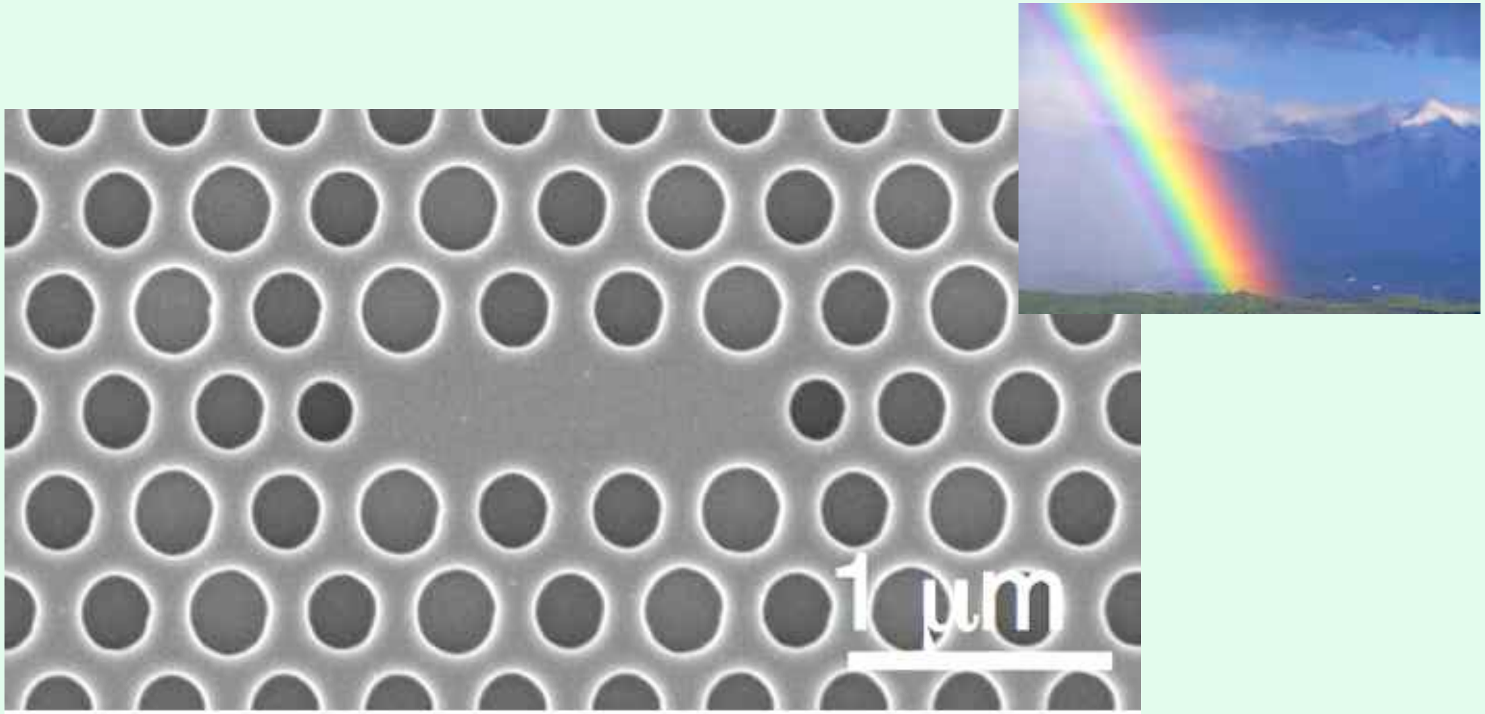


2. Solution: Internal lightsource

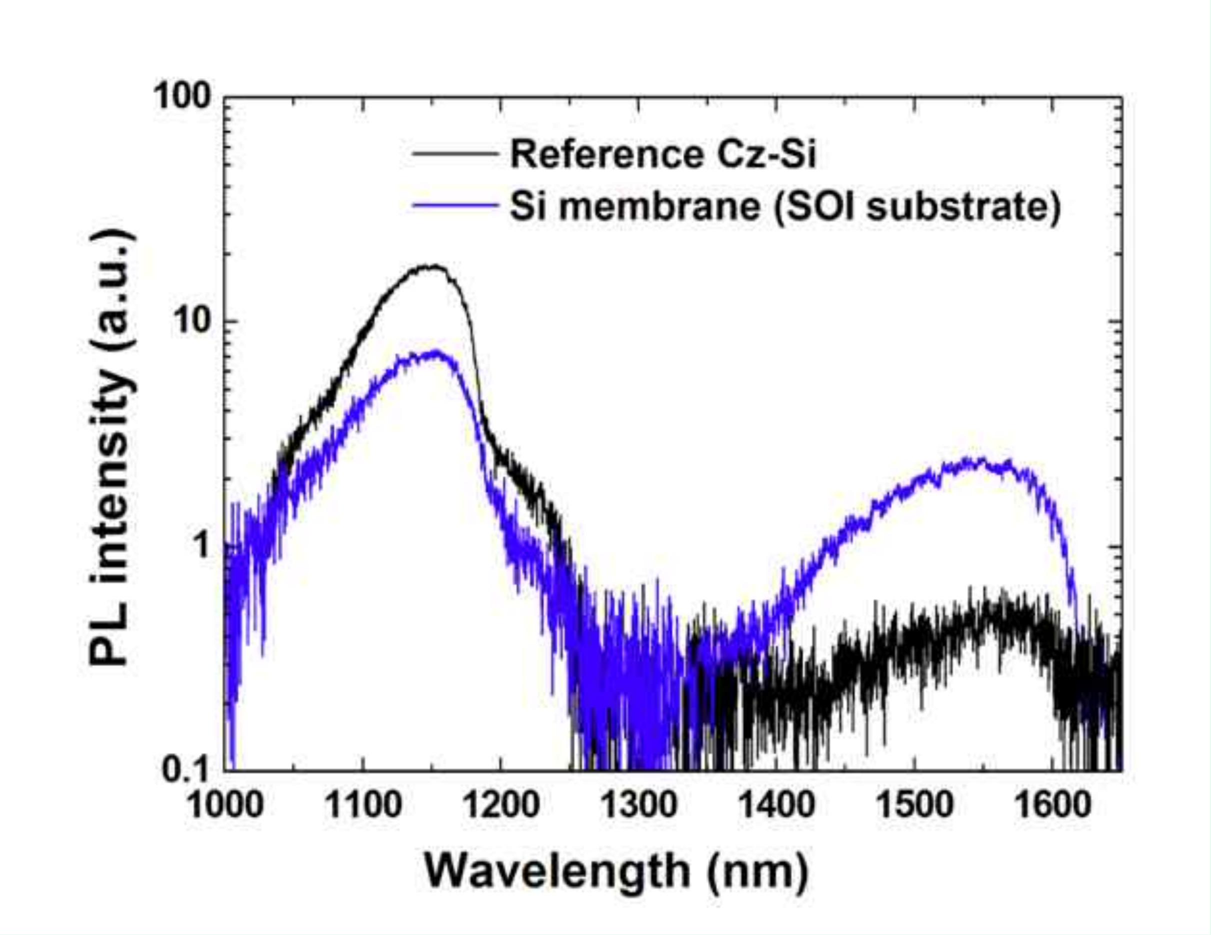




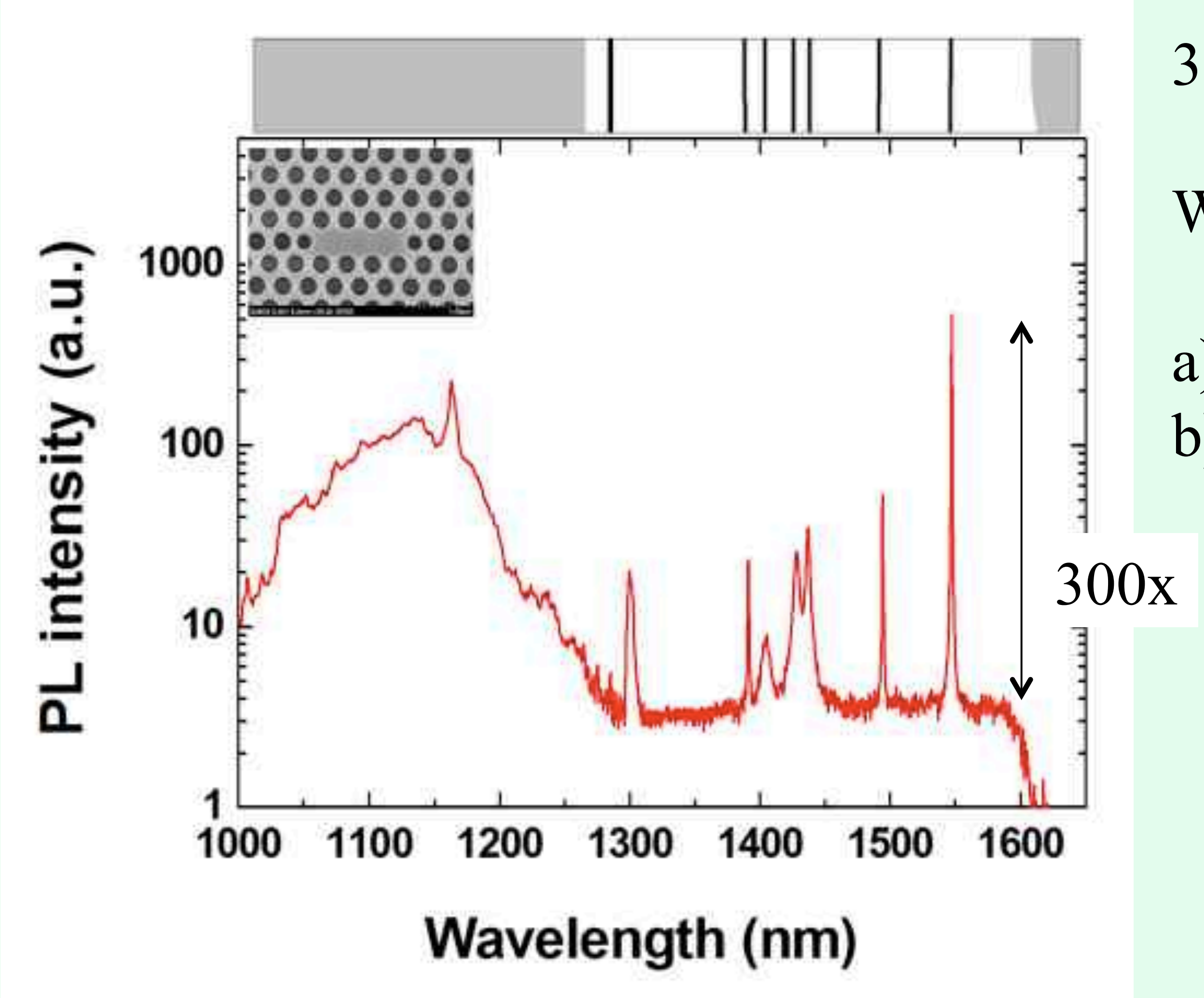
Defect luminescence



PL from SOITEC wafer



PL from SOITEC wafer + PhC Cavity



300x enhancement !!

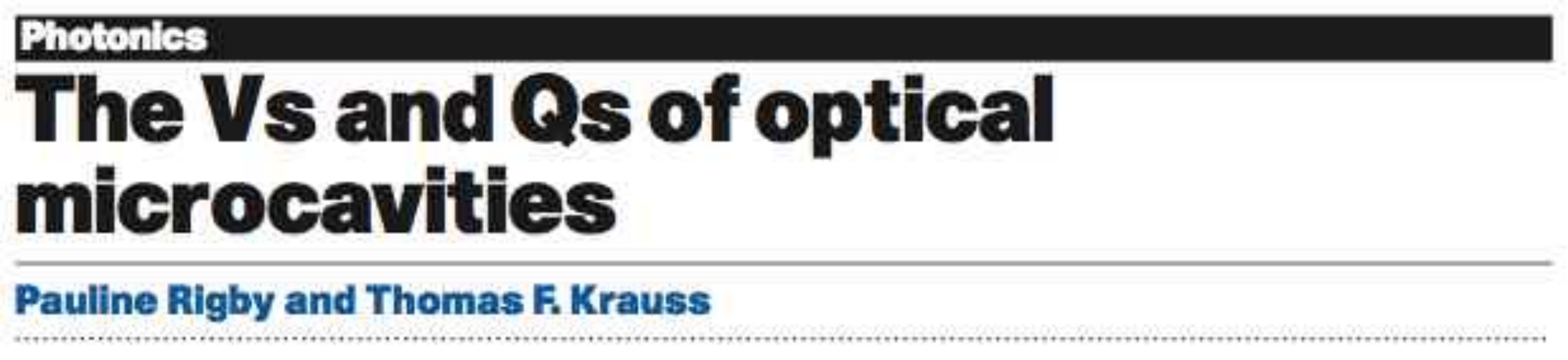
Why 300x ?

a) Purcell effect
b) Extraction efficiency

"Room-temperature emission at telecom wavelengths from silicon photonic crystal nanocavities", R. Lo Savio et al., Appl. Phys. Lett. 2011

St. Andrews Microphotonics

Purcell effect



Photonics

The Vs and Qs of optical microcavities

Pauline Rigby and Thomas F. Krauss

Nature News & Views, 1997

$$F_P = \frac{3\lambda^3}{4\pi^2}\frac{Q}{V}$$

$$\eta_{rad} = \frac{\tau_{nonrad}}{\frac{\tau_{rad}}{F_P} + \tau_{nonrad}}$$

E. M. Purcell, Phys. Rev. 69, 37 (1946).

Fermi’s Golden Rule

$$T_{i\to f} = \frac{2\pi}{\hbar}\left|\langle f \mid H' \mid i \rangle\right|^2 \rho$$

Density of states

Matrix element

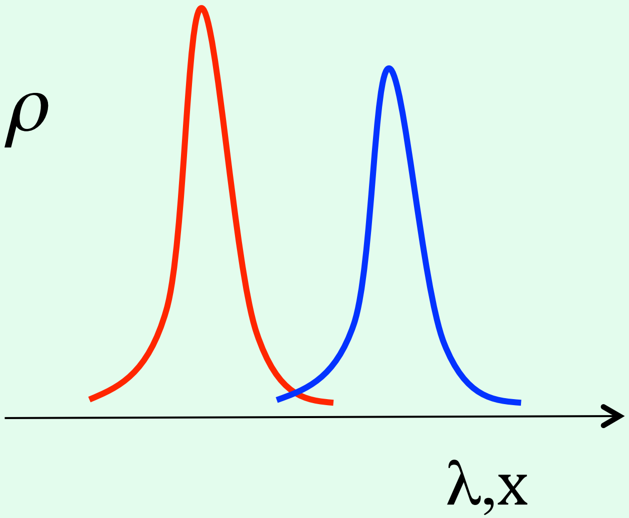
The Purcell factor relates to Fermi’s Golden Rule

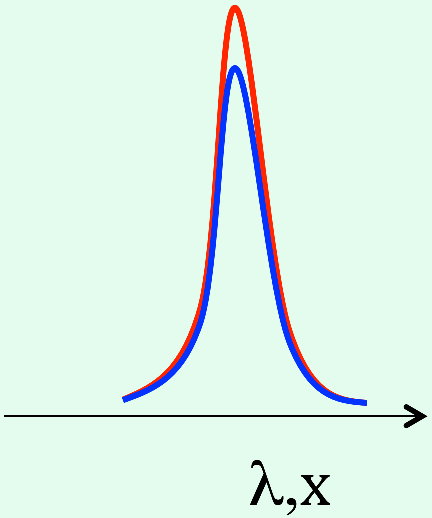
The transition between two quantum mechanical states is given by the product of the matrix element (derived from the Hamiltonian) and the density of final states.

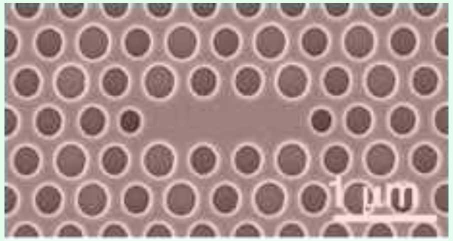
This transition probability is also called decay probability and is related to mean lifetime.

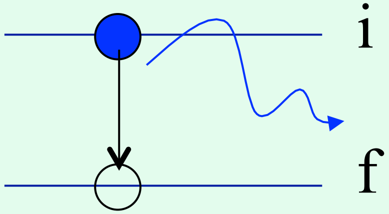
$$T_{i\to f} = \frac{2\pi}{\hbar}\left|\langle f \,|\, H' \,|\, i\rangle\right|^2 \rho$$

$$F_P = \frac{3\lambda^3}{4\pi^2}\frac{Q}{V}$$







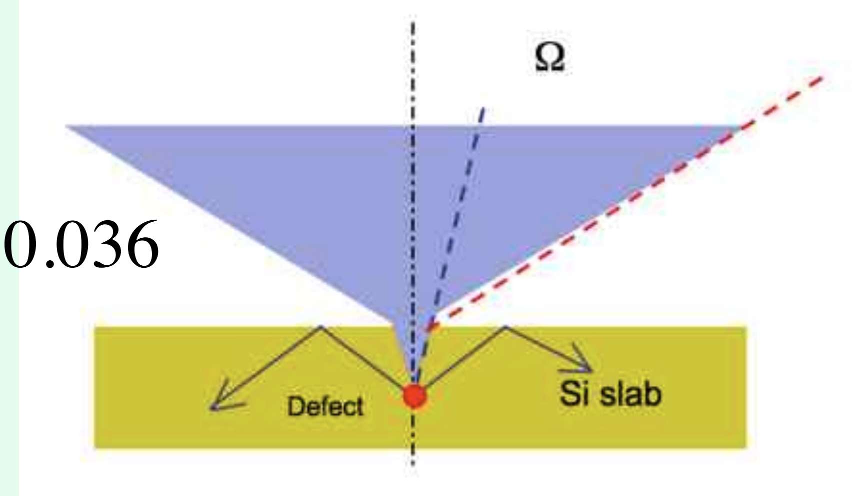


To enhance the interaction between a cavity and an emitter, they need to agree in emission wavelength and be in the same space -> Q/V

Extraction efficiency

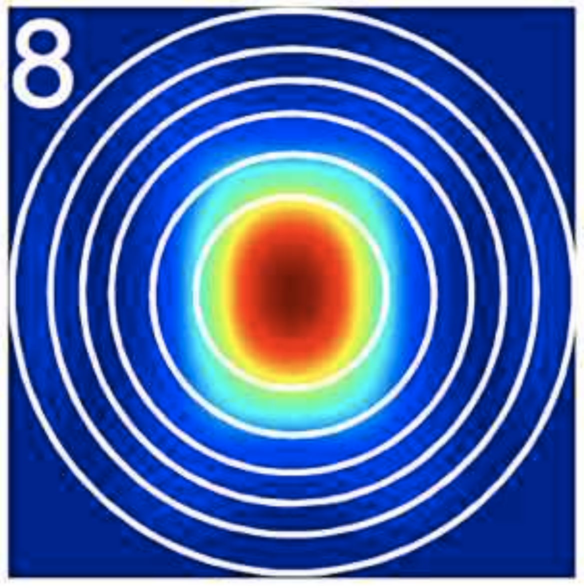
$$F_p = \frac{\gamma}{\frac{\eta_{cavity}}{\eta_{membrane}}}$$

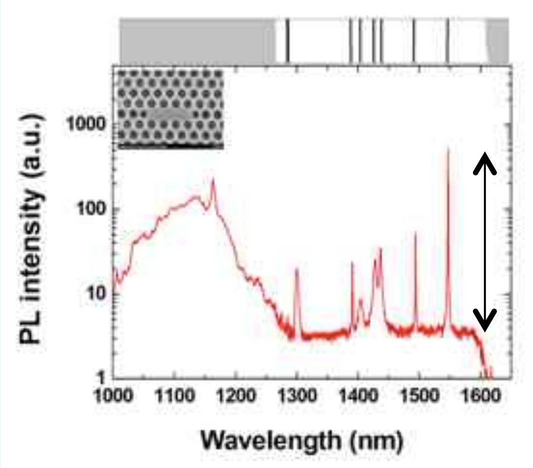
$$\eta_{membrane} = 0.036$$



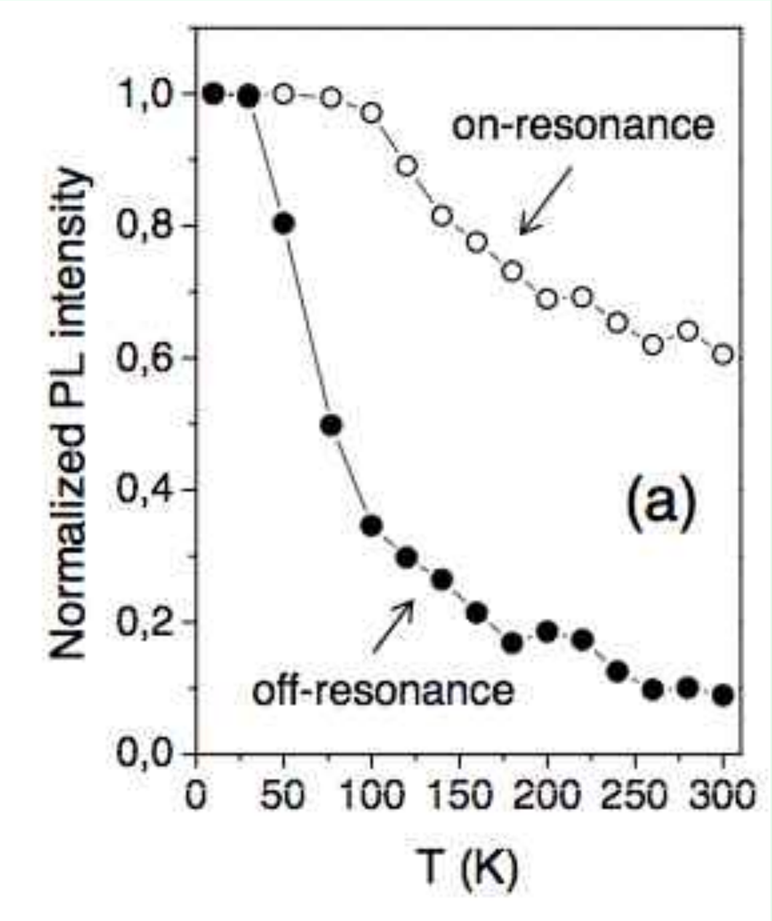
$$F_p = 12, \quad \eta_{ext} = 25$$

$$\eta_{cavity} = 0.9$$





$$\gamma = 300$$



$$\eta_{rad} = \frac{\tau_{nonrad}}{\frac{\tau_{rad}}{F_P} + \tau_{nonrad}}$$

The Purcell-factor makes defect emission “Room-temperatureable”

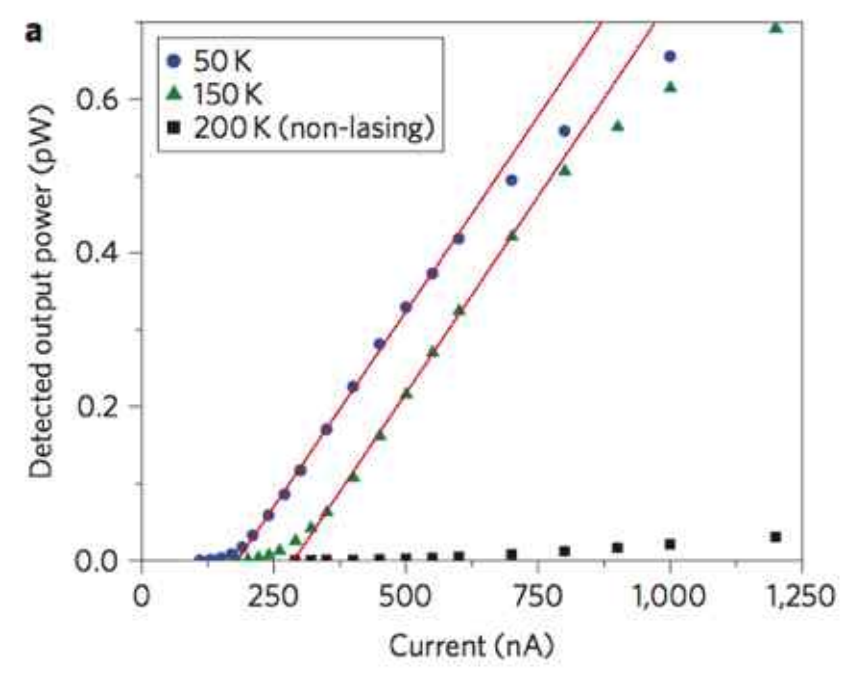
nature photonics

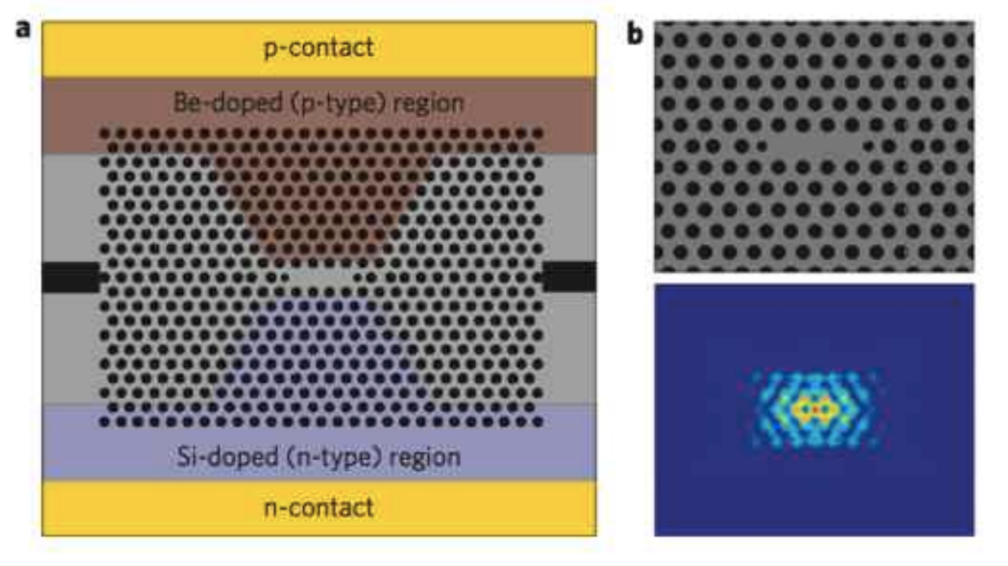
LETTERS

| DOI: 10.1038/NPHOTON.2011.51

Ultralow-threshold electrically pumped quantum-dot photonic-crystal nanocavity laser

Bryan Ellis[1], Marie A. Mayer[2,3], Gary Shambat[1], Tomas Sarmiento[1], James Harris[1], Eugene E. Haller[2,3] and Jelena Vučković[1]*

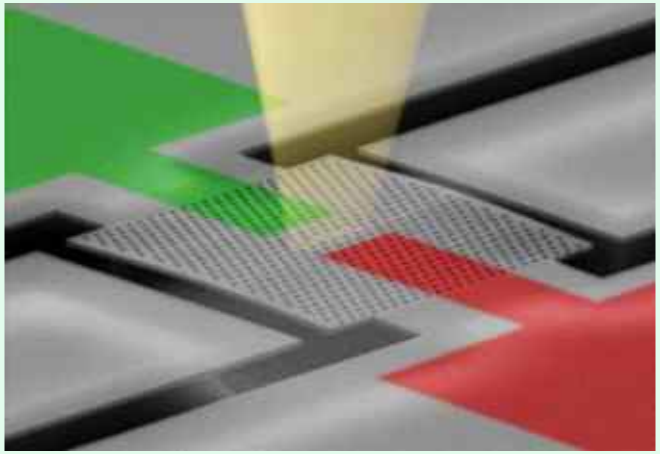




Conclusion light sources

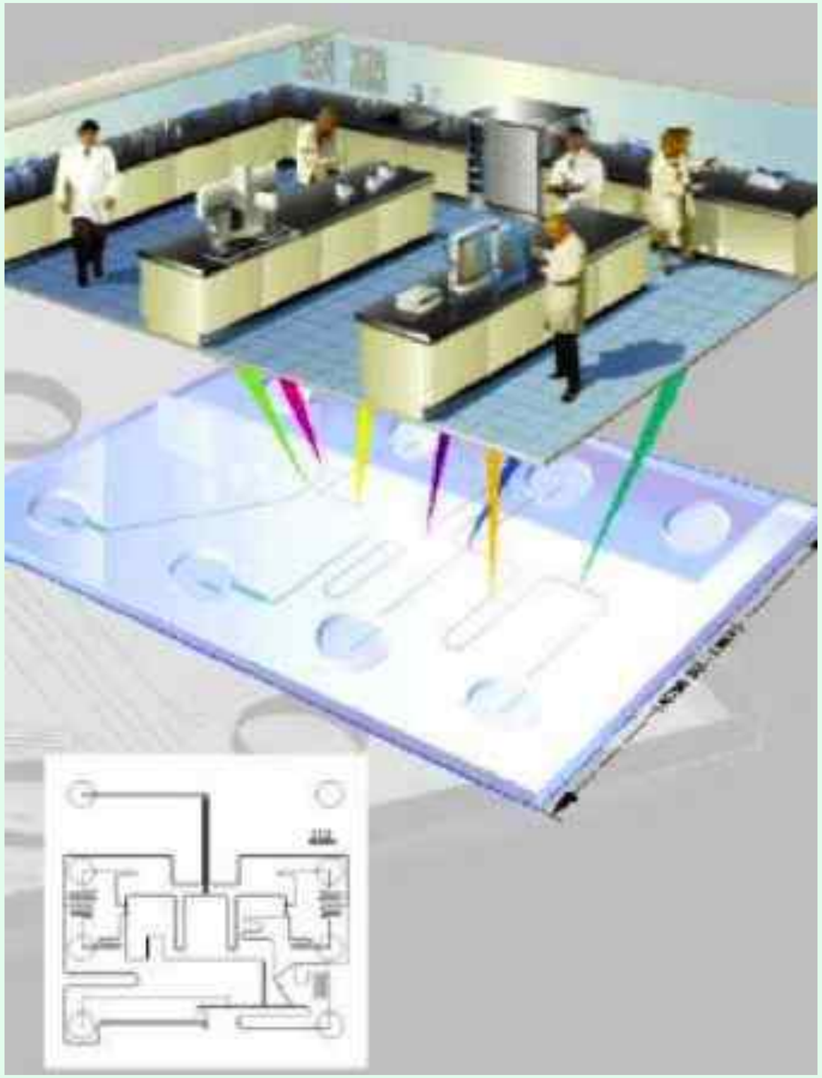
Using hydrogen treatment and well-designed designed photonic crystal cavities, we can achieve significant light emission directly from silicon. This is not yet sufficient for optical interconnects, but further improvements are possible.

The output power is competitive with comparable III-V devices,. although not with III-V materials as such.



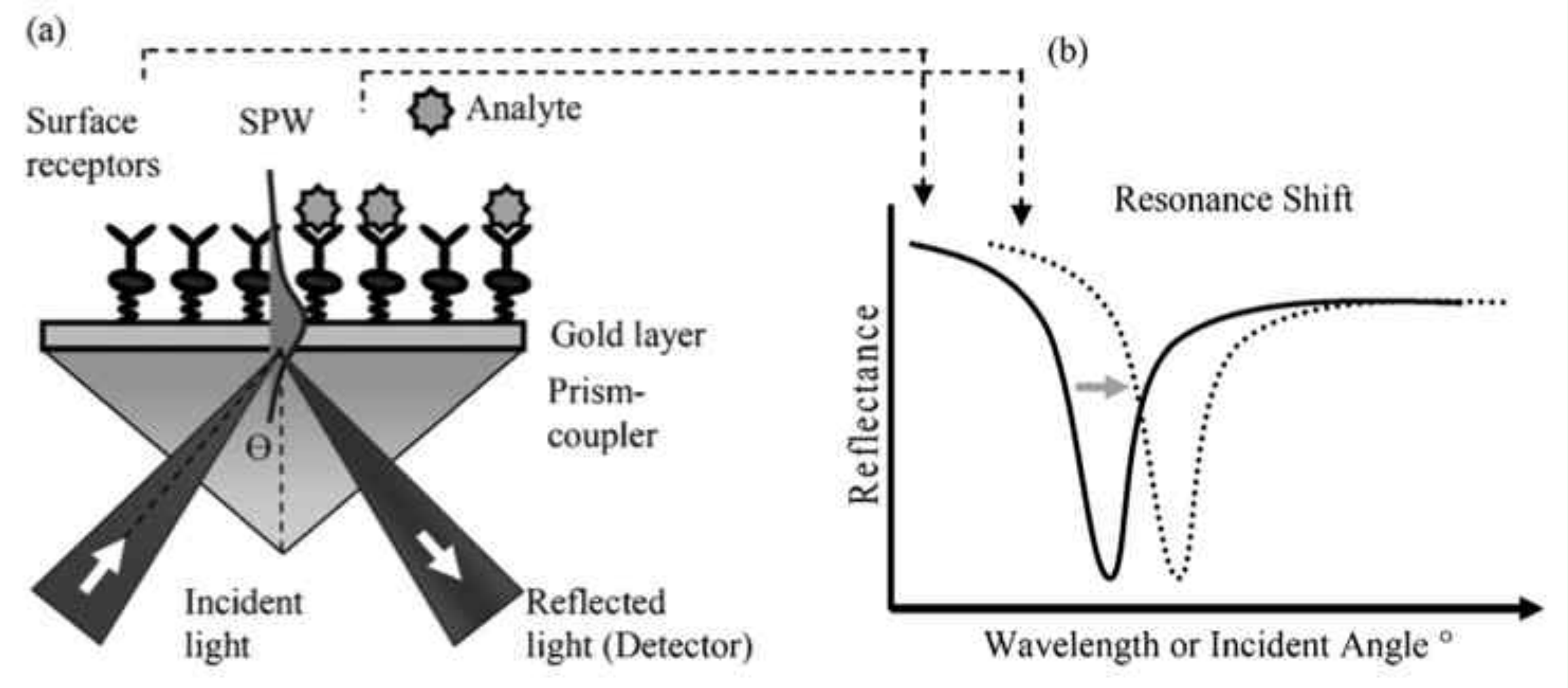
2. Silicon Nanophotonics for Biosensors

Lab on a chip (LoC)



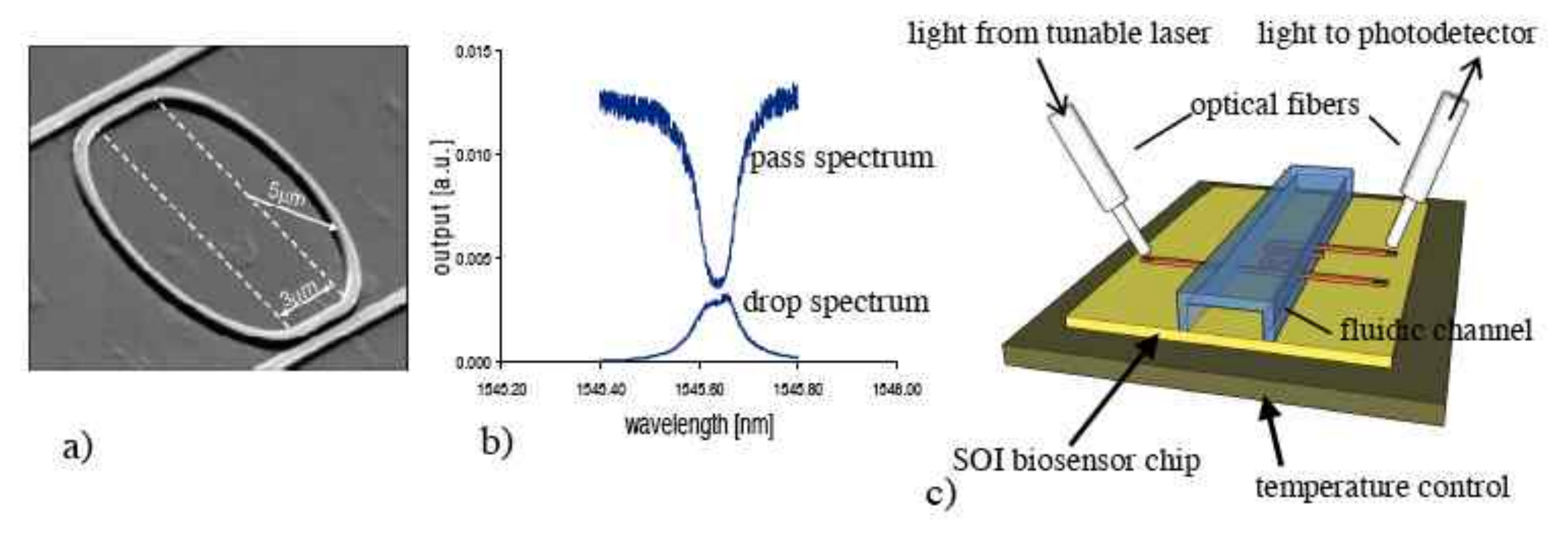
The Lab on a chip (LoC) concept aims to realise biochemical analysis/synthesis in a miniaturised format.

Surface Plasmon sensor



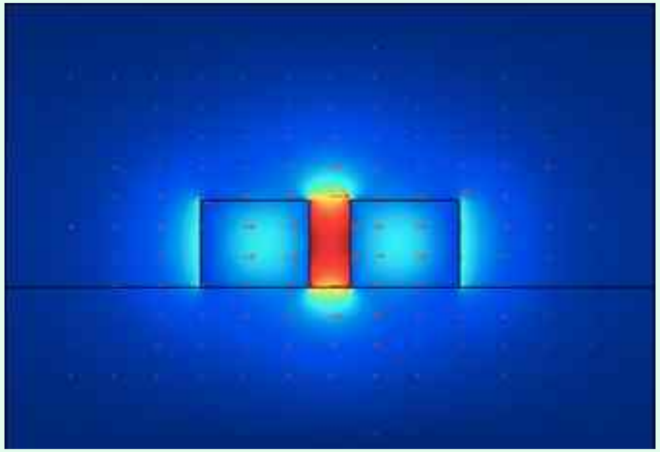
Very high sensitivity -> Biacore
Broad resonance

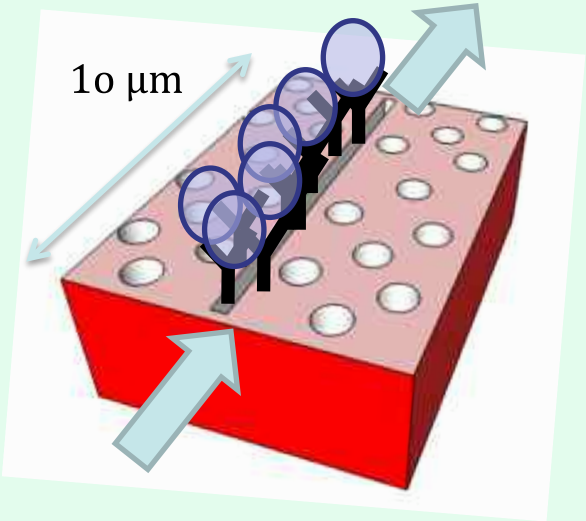
Silicon ring resonator as biodetector



Lower sensitivity
Narrow resonance -> Genalyte

K. deVos, R. Baets et al., OPTICS EXPRESS 15, pp. 7610-7615 (2007).

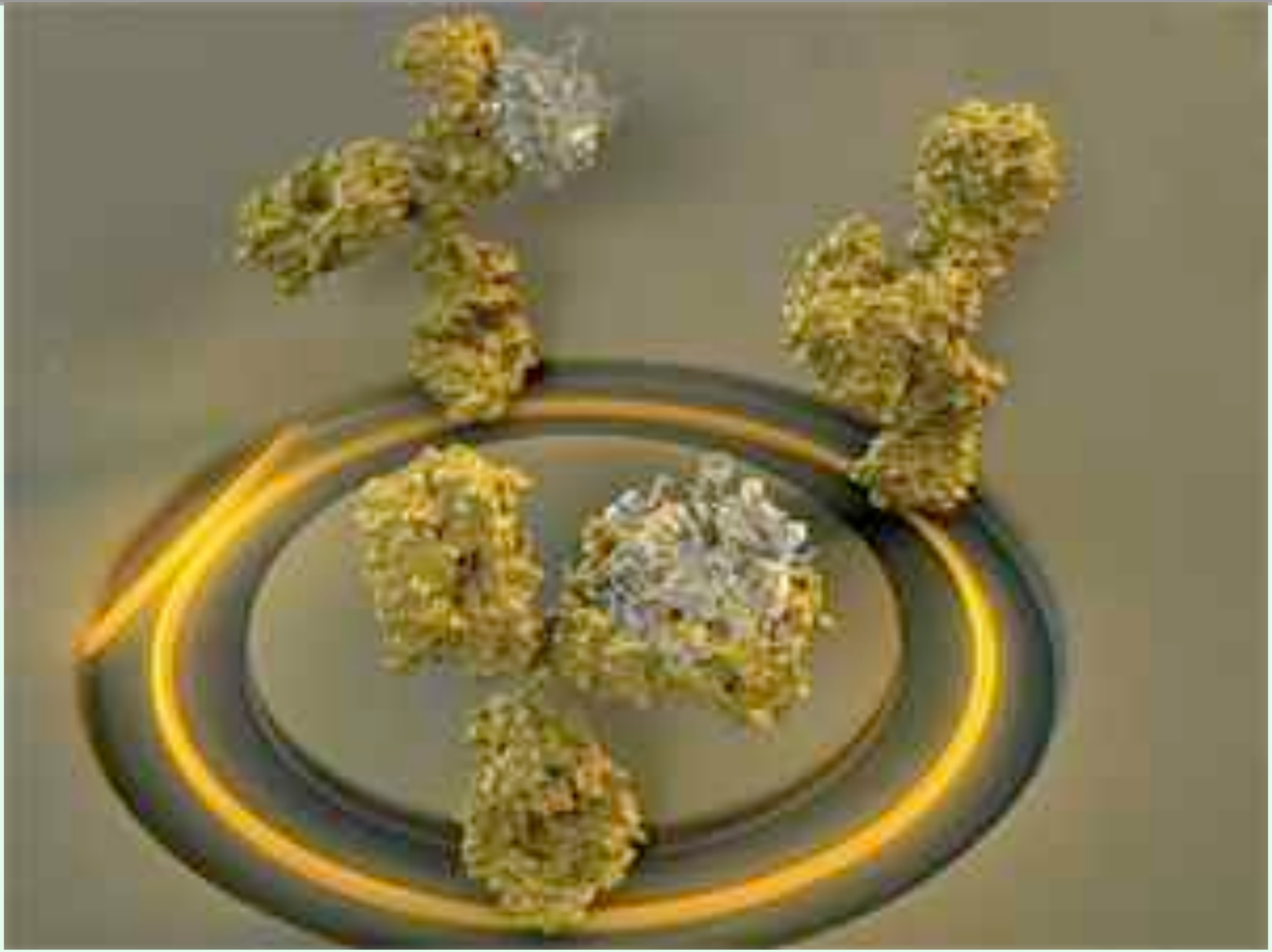




High sensitivity
Narrow resonance -> ???

Di Falco, Krauss et al., APL 2009

Genalyte



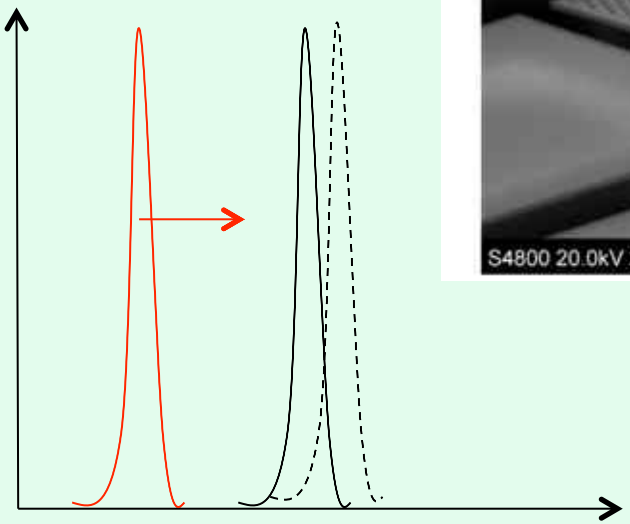
Chip in a lab

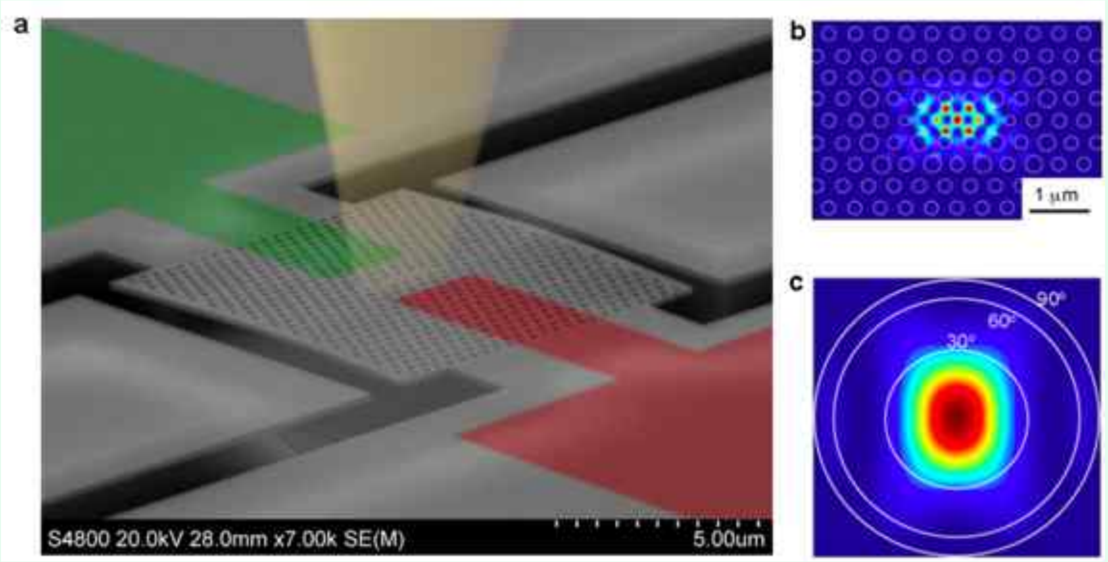
Light source

Spectrum Analyser

Transducer

Source





The possible integration of silicon light sources would lead to miniaturisation, large scale integration and simplicity.

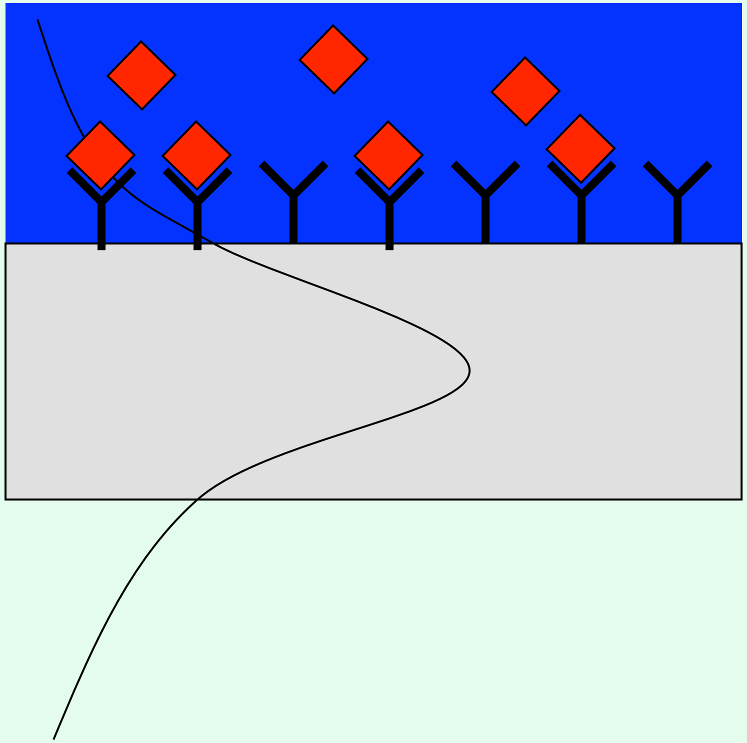
Lab on a chip

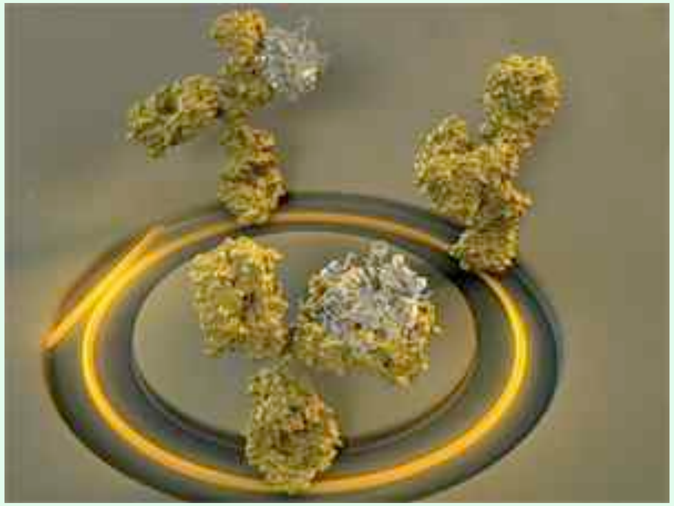
Light source

Spectrum Analyser

Autonomous sensors

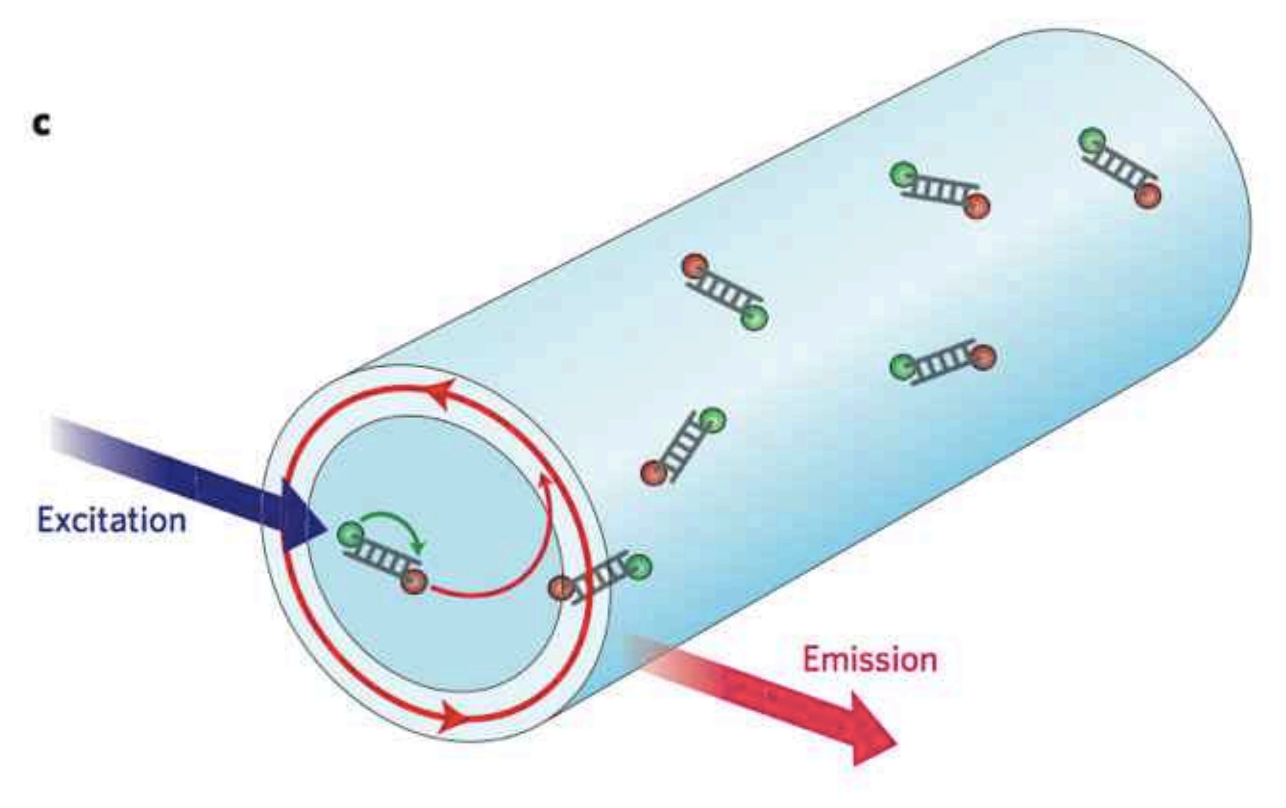
2nd problem: Diffusion time





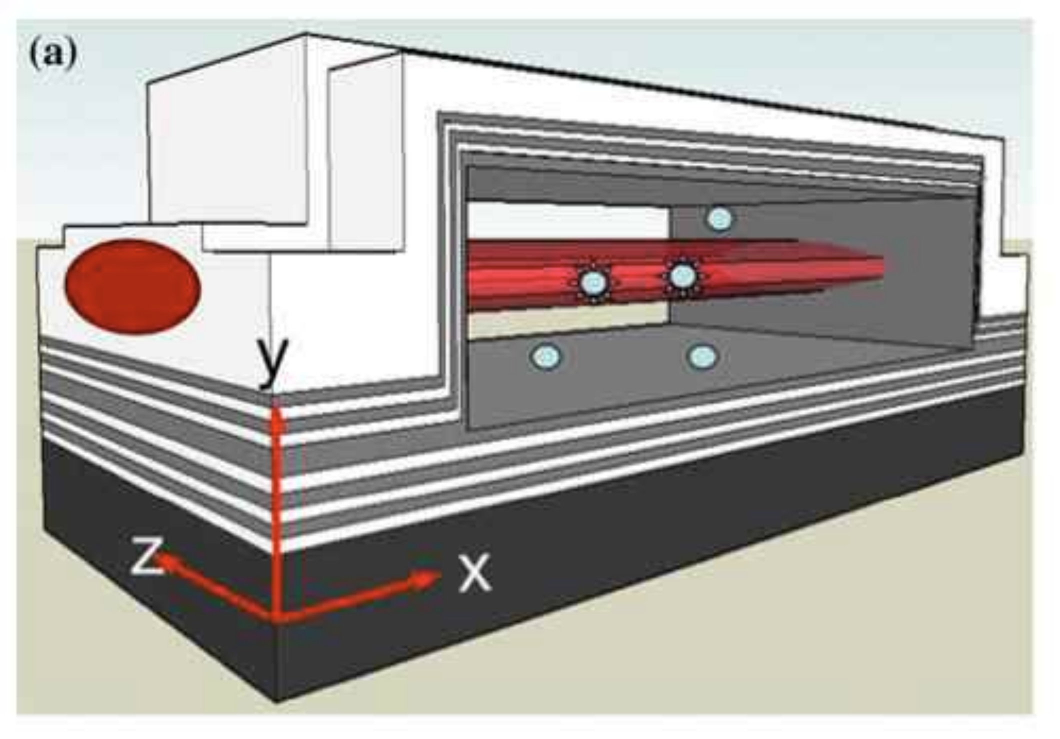

Watchout Commodities

Optofluidic laser



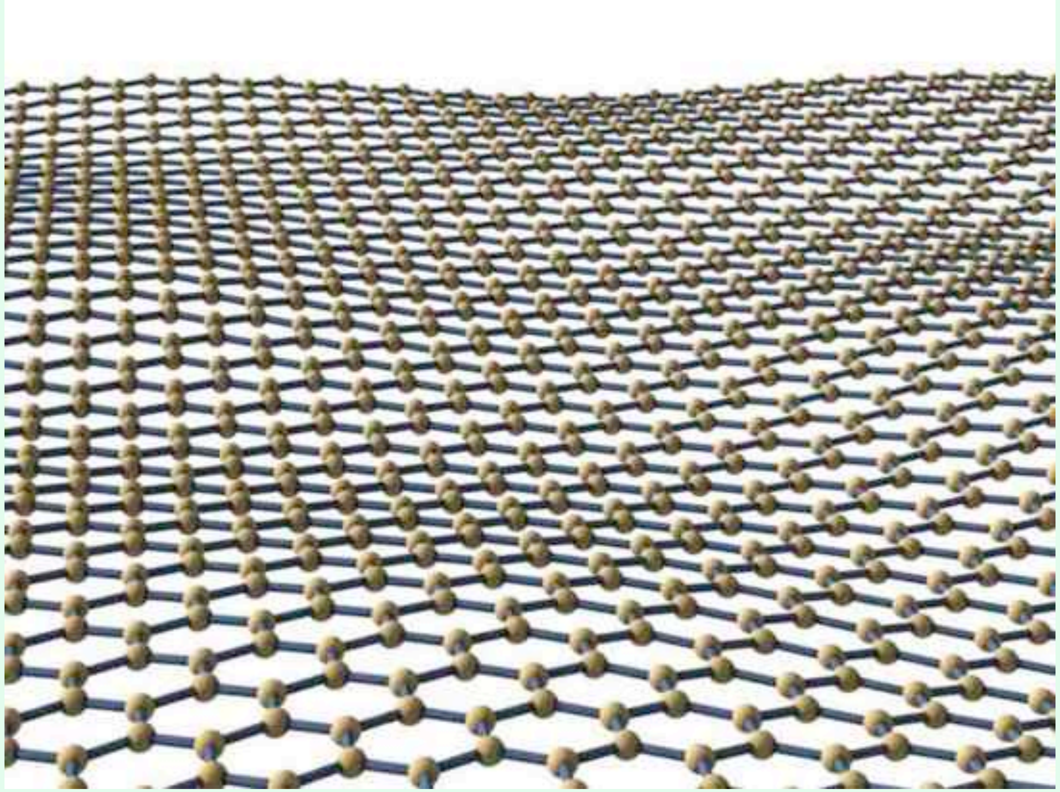
H Schmidt & AR Hawkins, Nature Photonics August 2011

Fluorescence correlation spectroscopy (FCS), FRET,…
Measure changes caused by molecular binding, not using the surface.



H Schmidt & AR Hawkins, Microfluidics & Nanofluidics (2008)

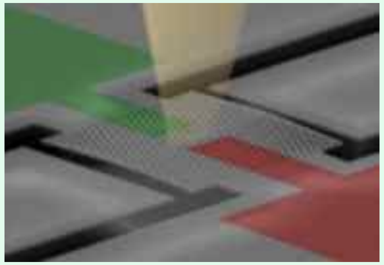
Graphene

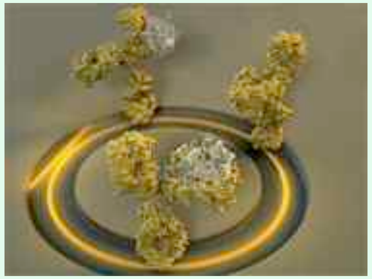


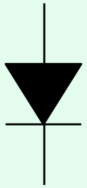
As it does not have volume, only surface, its entire structure is exposed to its environment and responds to any molecule that touches it. This makes it a good material for super-sensors capable of detecting single molecules of toxic gases.

Key issues Biology

1. Lab on a chip – chip on a lab: Integration.







2. Move away from surface affinity biosensor. Novel integrated sensor architectures.