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NANO-PHOTONIC INTEGRATED CIRCUITS the promise and the problems

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OUTLINE

- Introduction to nano-photonics
- Nano-photonic ICs
- Challenges
  - in the physics
  - in the technology
  - in the packaging

Nano-photonics: what?

Photonics:

generation, transport, processing and detection of light

Nano-photonics:

same, whereby light interacts with material features with a scale in the range of a few nm to a few 100 nm (in (one,) two or three dimensions)

Nano-photonics: a broad field

- **linear and non-linear response of nano-composite materials**
    - **size of nano-particles<< l ® effective medium**
    - **strong surface plasmon resonant enhancement for metallic nanoparticles**
    - **potential of very strong $c^{(3)}$ (plasmon enhancement)**
- **interband transitions in semiconductor nanoparticles**
    - **quantum dots and wires (size << l)**
    - **strong modification of electronic bandstructure**
    - **potential of strong $c^{(3)}$ (electronic enhancement)**
- **wavelength scale high refractive index contrast structures**
    - **modification of SpE in wavelength scale microcavities**
    - **modification of propagation by means of photonic crystals**
    - **ultra-compact photonic circuits, photonic crystal fiber**
    - **potential of strong $c^{(3)}$ (optical enhancement)**

THIS PRESENTATION

OUTLINE

- Introduction to nano-photonics
- Nano-photonic ICs
- Challenges
  - in the physics
  - in the technology
  - in the packaging

Photonic Integrated Circuits (PICs)

What ?

- ICs in which sub-components are interconnected by optical waveguides
- sub-components :
  - passive wavelength selective components
  - electrically driven modulators, light sources, optical amplifiers, detectors, wavelength converters…
  - ...
- fabrication by wafer-scale micro-electronic technologies

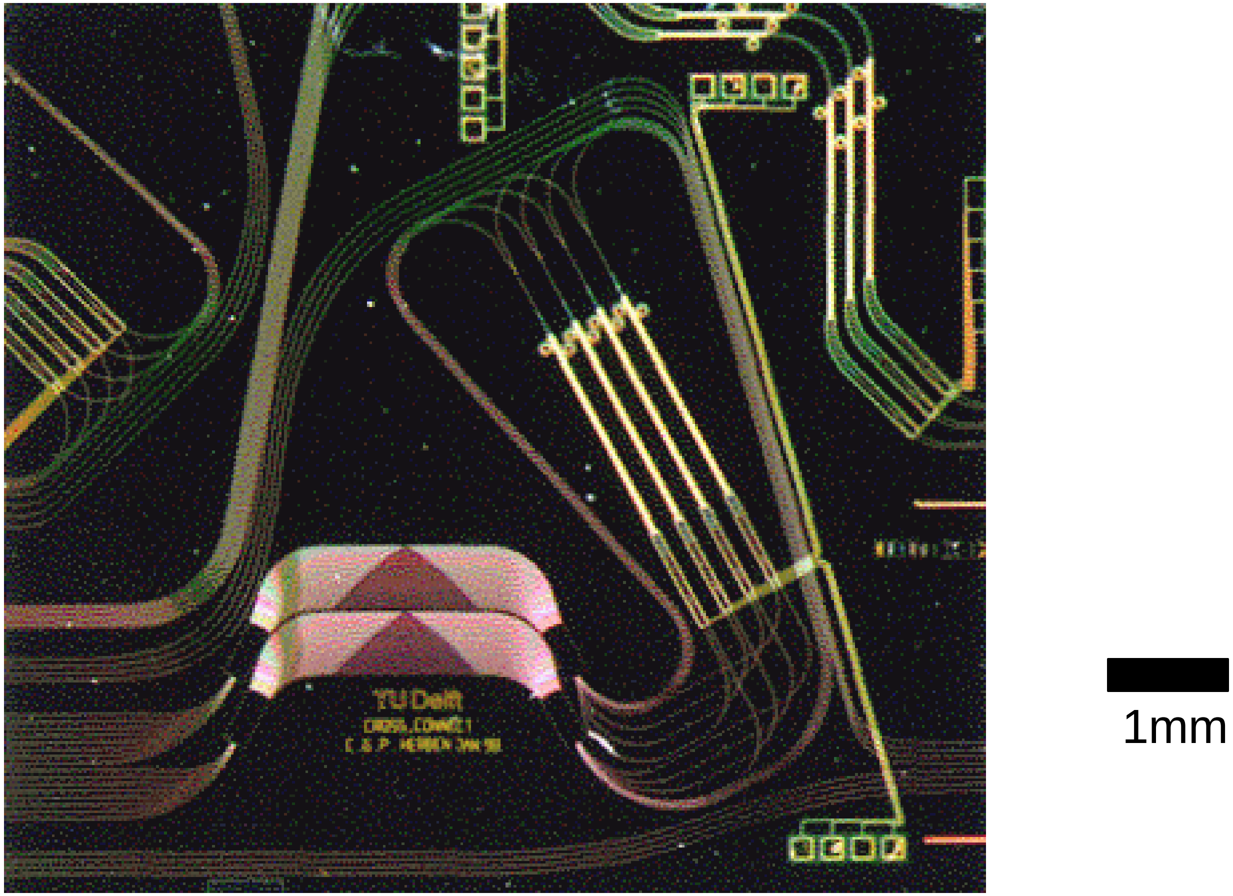
Photonic Integrated Circuits

Why integrate ?

- Economics of wafer scale integration
- Compact implementation of complex functions (systems-on-a-chip)
- Higher performance
- **!!! Alignment of photonic components automatically ensured by lithographic methods !!!**

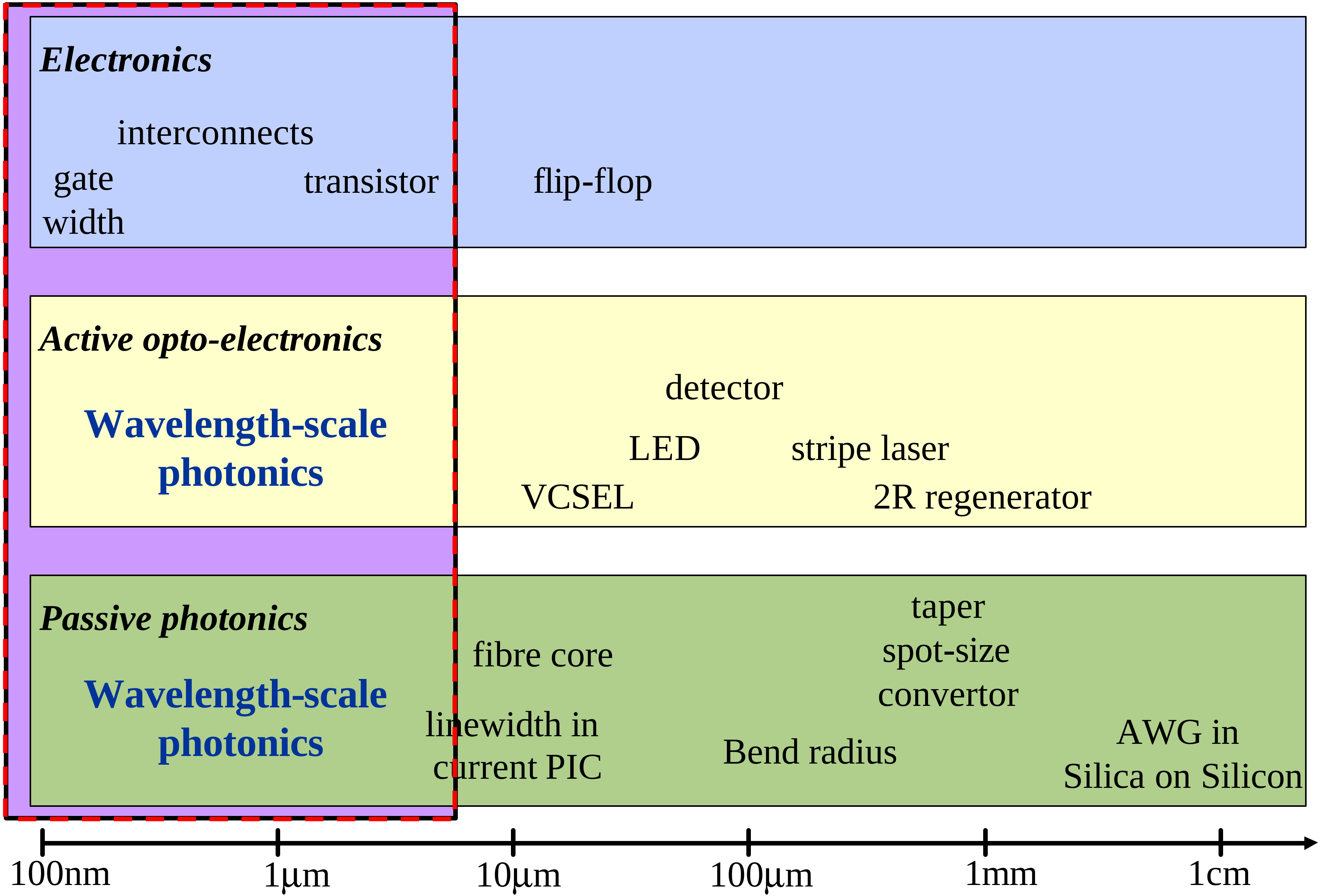
Crossconnects

E.g. Double-PHASAR X-connect (TU Delft)



Ref.: Herben et al., IEEE PTL 10(5), pp. 678-680 (1998)

Scale difference



Electronics

interconnects

gate width

transistor

flip-flop

Active opto-electronics

Wavelength-scale photonics

detector

LED

stripe laser

VCSEL

2R regenerator

Passive photonics

Wavelength-scale photonics

taper

spot-size convertor

fibre core

linewidth in current PIC

Bend radius

AWG in Silica on Silicon

PICs: today and future

Today (InP, Silica-on-Silicon...):

- **size of components on a chip (both functional components and interconnect components):**

$10^3 - 10^6\ \mu m^2$

- **number of components on a chip:**

$1 - 10^3$

Future (10-20 years from now):

- **size of components on a chip (both functional components and interconnect components):**

$1 - 10^3\ \mu m^2$

- **number of components on a chip:**

$10^3 - 10^6$

Reduce PIC-size / increase density

WE NEED:

Ultra-compact waveguiding with

- Sharp bends (Bend radius < 10μm)
- Compact splitters and combiners
- Short mode-conversion distances

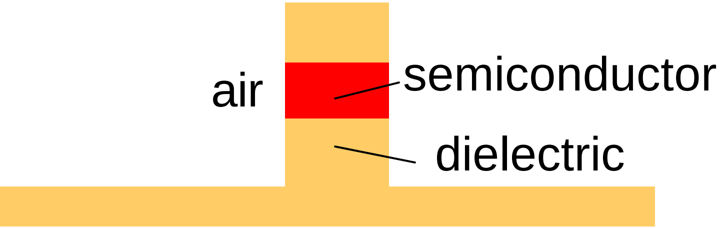
Compact wavelength selective functions

- Highly dispersive element
- Small, high-Q resonators

Compact non-linear functions

- Increase power density by using tight confinement

High refractive index contrast (>2:1)



High refractive index contrast allows for:

- **very tight bends**
- **compact resonators with low loss**
- **wide angle mirrors**
- **very compact mode size**
  - **--> strong field strength**
    --> strong non-linear effects
  - **--> small volume to be pumped in active devices**
    --> faster and/or lower power
- **photonic bandgap effects**

® high refractive index contrast is the key for ultra-compact photonic circuits

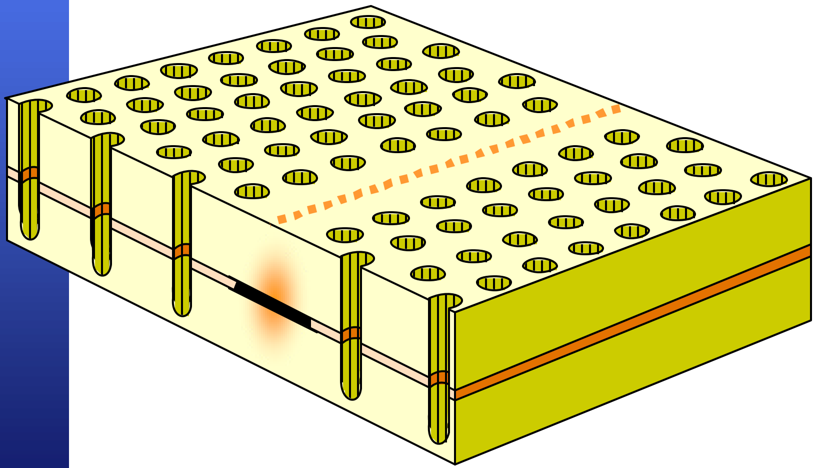
Ultra-compact waveguide candidates

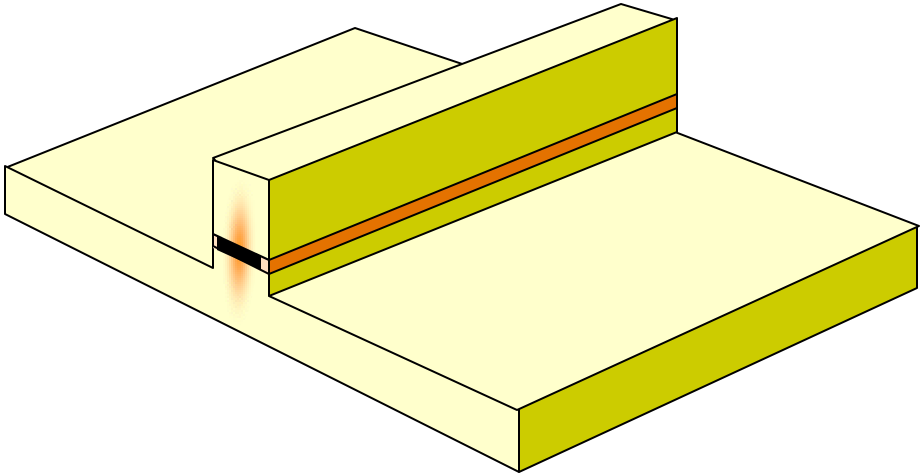
Photonic Crystal waveguides:

- in-plane: **high contrast** photonic crystal defect
- out-of-plane: TIR

Photonic Wires:

- in-plane: **high contrast** TIR
- out-of-plane: TIR





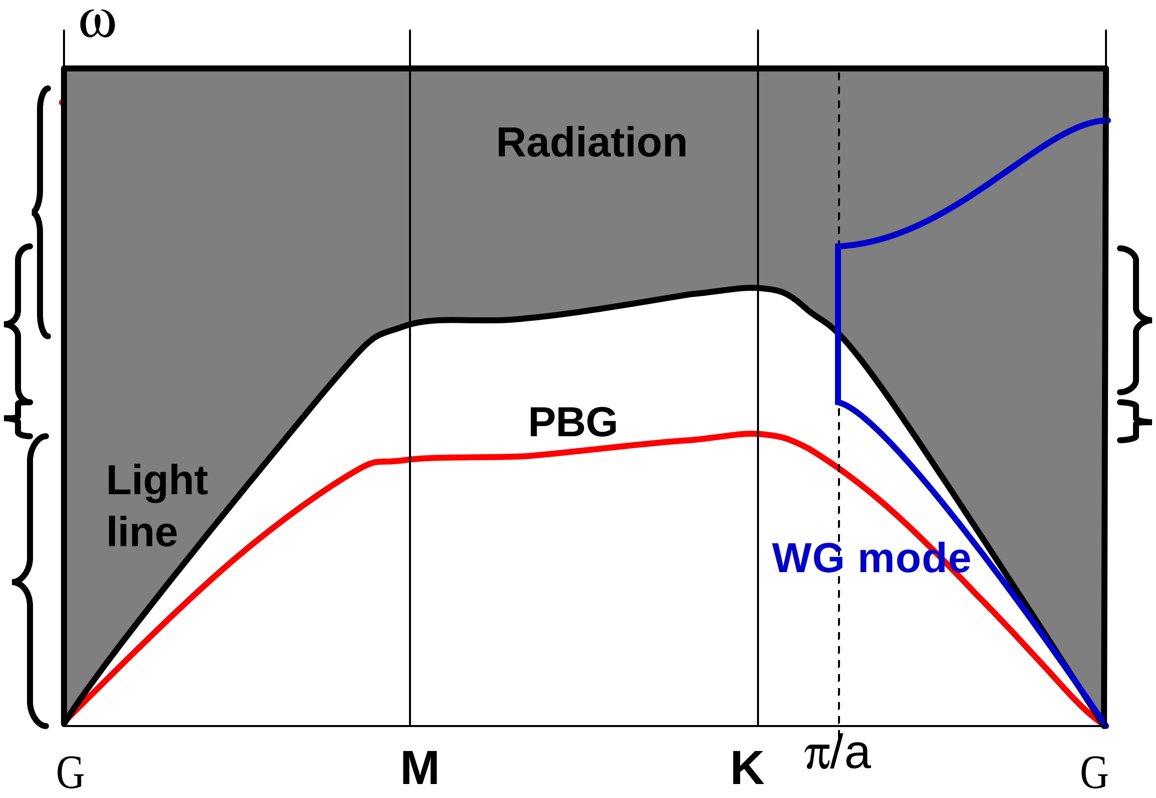
Guided Bloch mode conditions

leak into substrate

Coupling forw/backw

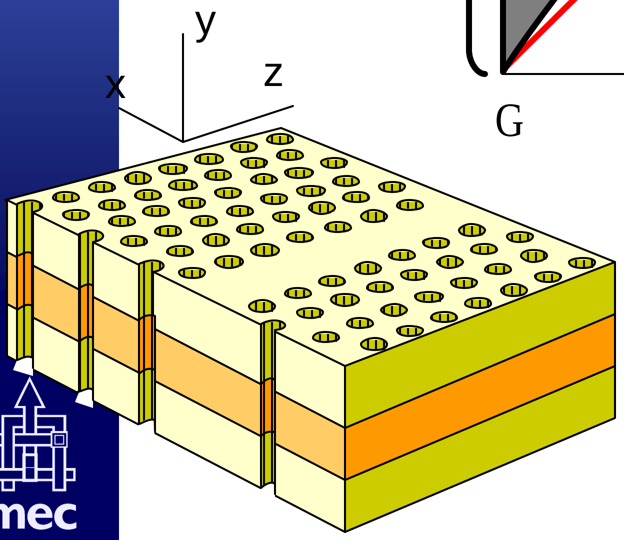
guiding by PhC & SWG

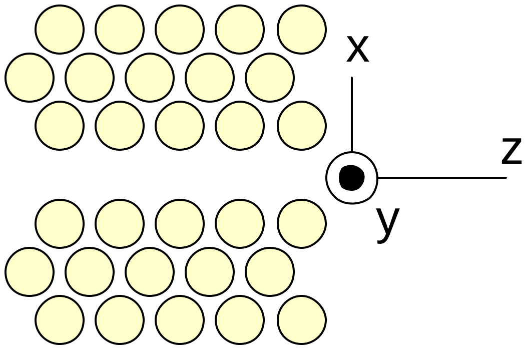
leak into PhC

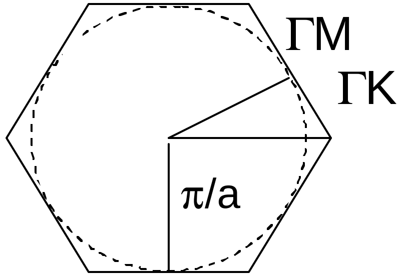


Waveguide PBG

Guided Bloch Mode







Brillouin Zone

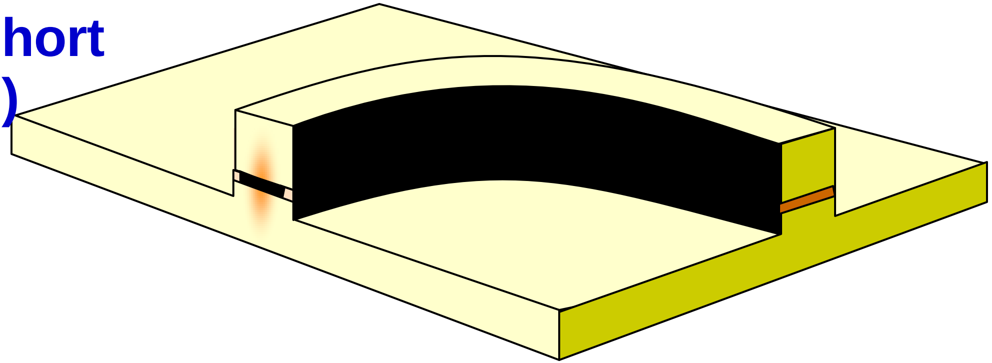
Compact bends

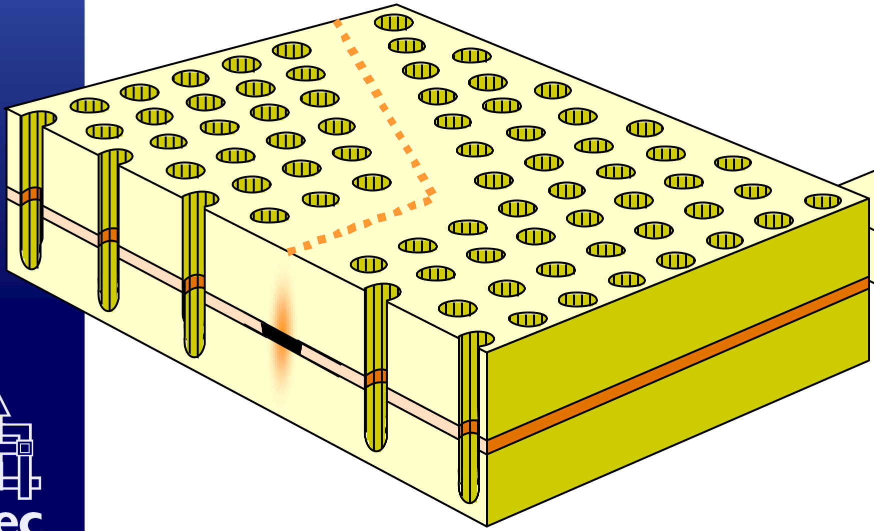
Photonic Crystal

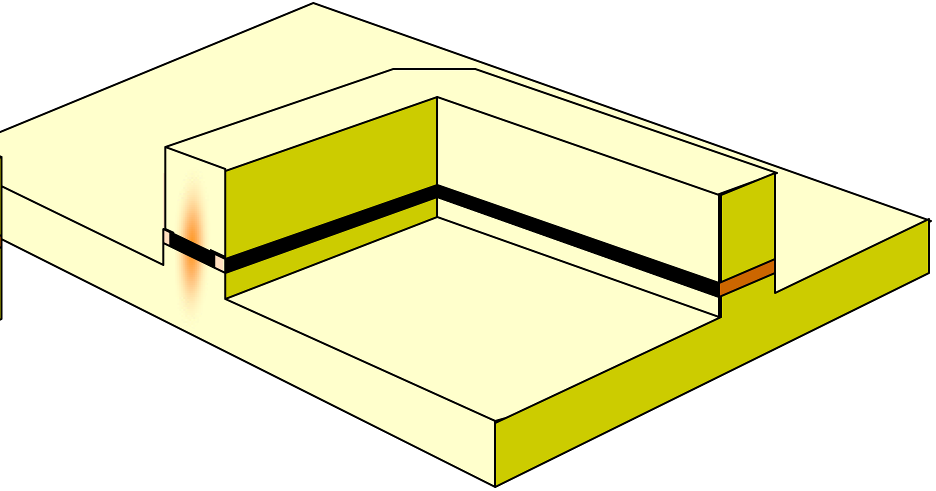
- **Light is confined by the PBG**

Photonic Wire

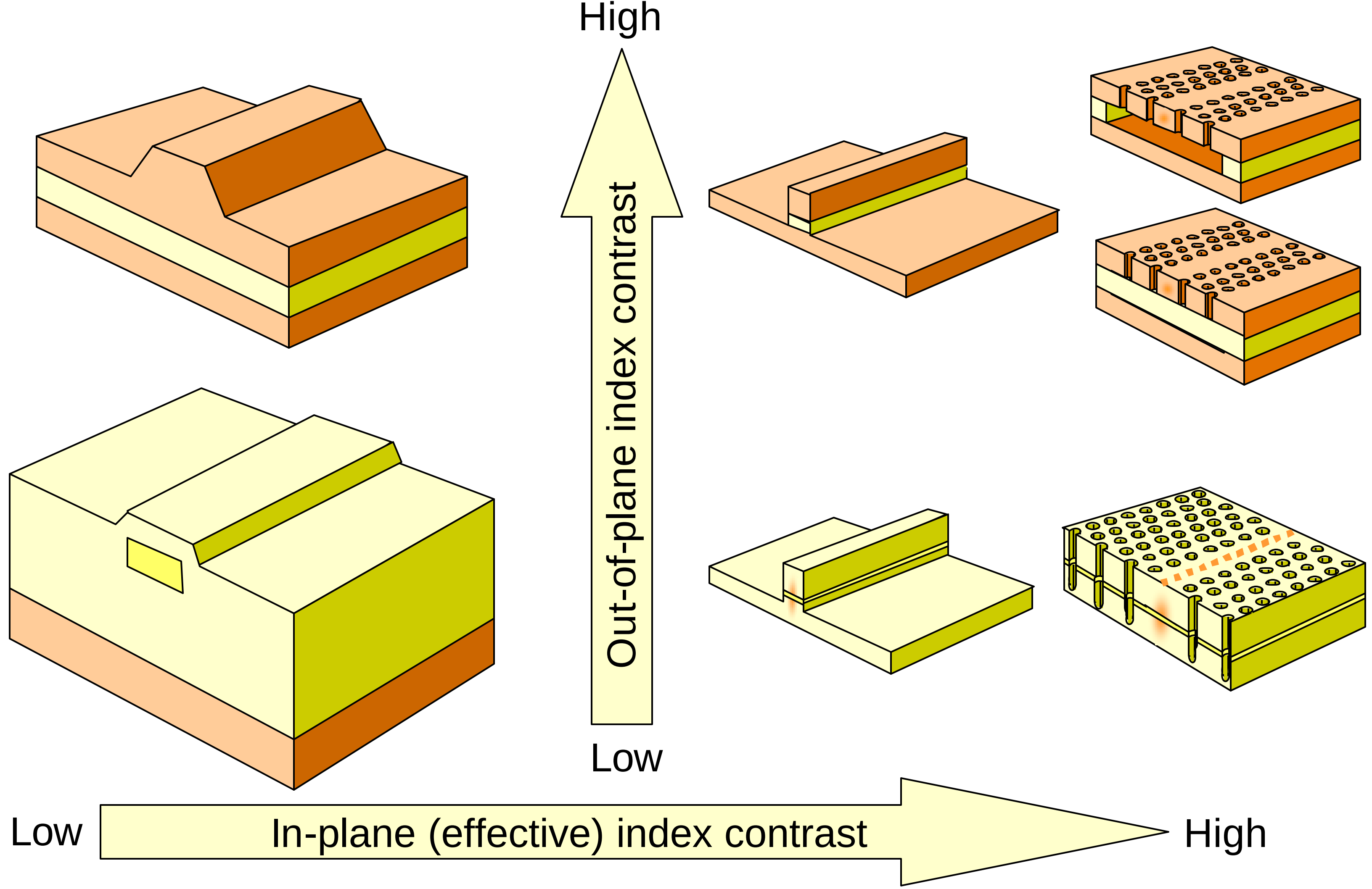
- **Deep etch allows for short bend radius (a few μm)**
- **Corner mirrors**







Index Contrast



Conventional PICs

Nanophotonics

High

Out-of-plane index contrast

Low

Low

In-plane (effective) index contrast

High

Materials for nanophotonic waveguides

	In-plane index contrast	Out-of-plane index contrast
Si/SiO_2 (SOI)	3.5 to 1	3.5 to 1.5
Si/air (membrane)	3.5 to 1	3.5 to 1
GaAs/AlOx	3.5 to 1	3.5 to 1.5
InP/SiO_2	3.3 to 1	3.3 to 1.5
$SiON/SiO_2$	2 to 1.5/1	2 to 1.5
GaAs/AlGaAs	3.5 to 1	3.5 to 3.2
InGaAsP/InP	3.3 to 1	3.3 to 3.17

Spectral accuracy and geometrical accuracy

High index contrast components:

- interference based filters,

$$\boxed{\frac{\partial l}{l} \approx \frac{\partial d}{d}}$$

with d the waveguide width (» l)

- cavity resonance wavelength

$$\boxed{\frac{\partial l}{l} \approx \frac{\partial d}{d}}$$

with d the cavity length (a few l)

- photonic crystal

$$\boxed{\frac{\partial l}{l} \approx \frac{\partial d}{d}}$$

with d the hole diameter (» l)

if tolerable wavelength error : 1 nm

ß

tolerable length scale error : (of the order of) 1 nm

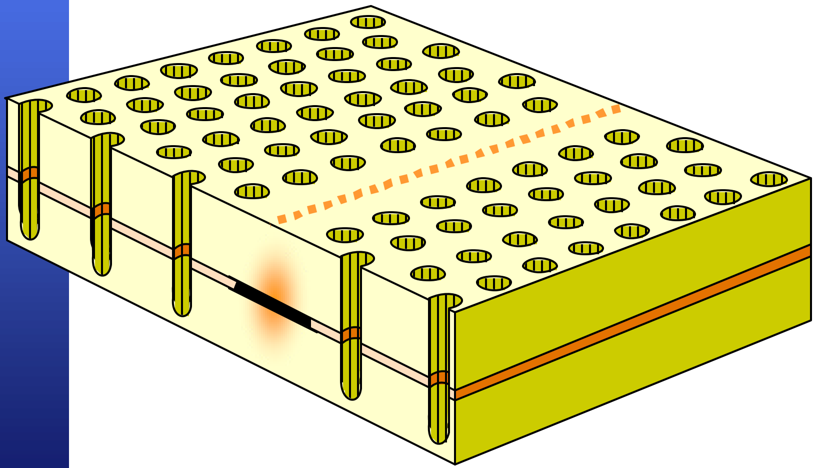
Ultra-compact waveguide candidates

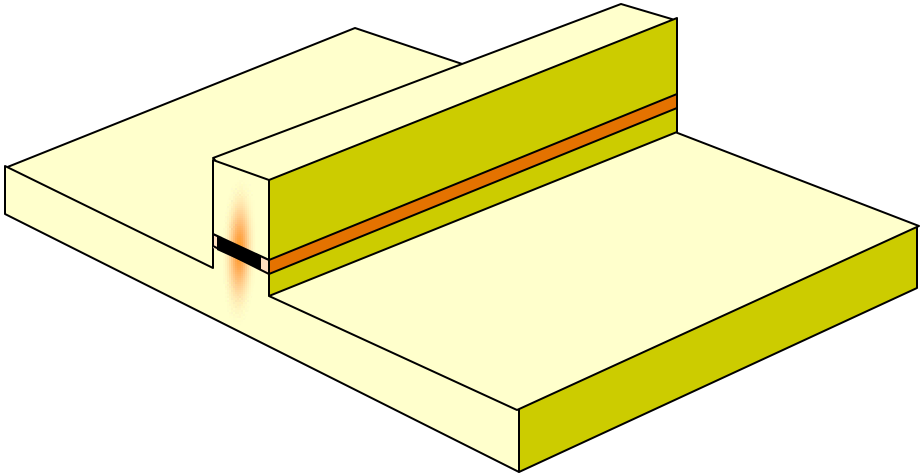
Photonic Crystal waveguides:

- in-plane: **high contrast** photonic crystal defect
- out-of-plane: TIR

Photonic Wires:

- in-plane: **high contrast** TIR
- out-of-plane: TIR



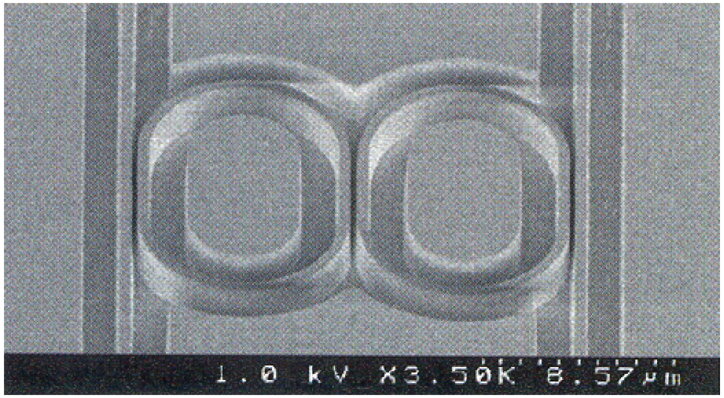


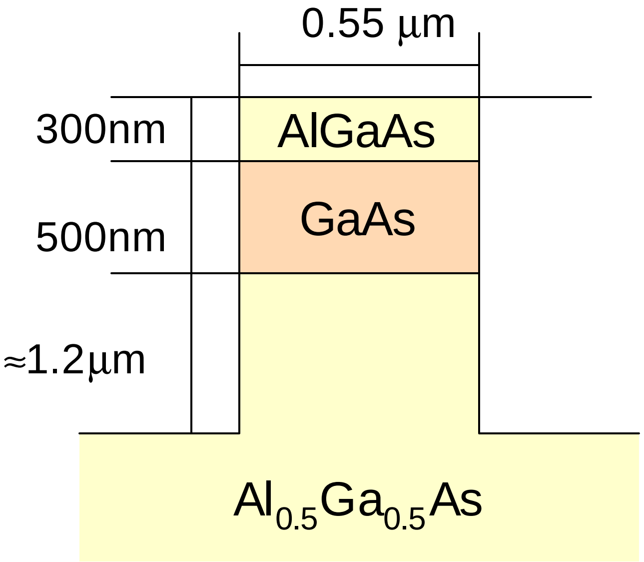
Both cases:
• feature size : 50-500 nm
• required accuracy of features: 1-10 nm
NANO-PHOTONIC waveguides

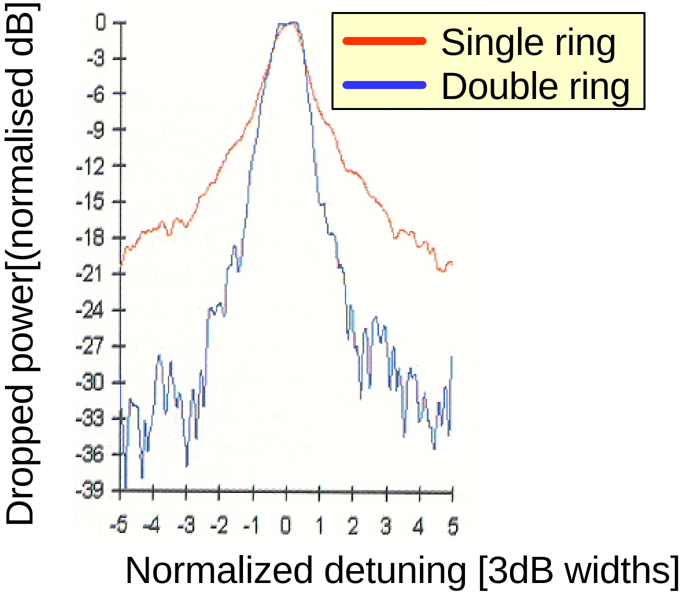
Ring resonator based add-drop filter

Hryniewcz et al.

- **Waveguide width: .42-.62mm**
- **Straight guides: <10 dB/cm**
- **Bend radius: 4.5 mm**







Ref.: Hryniewicz et al., IEEE PTL 12, pp. 320 (2000)

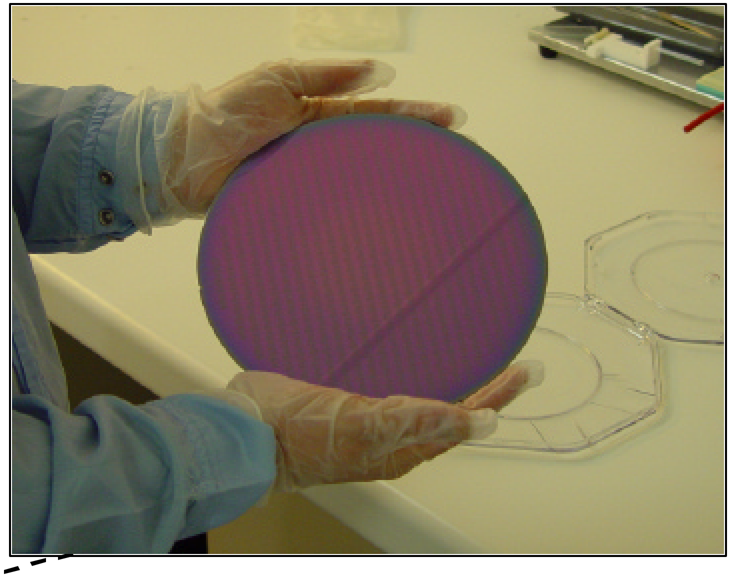
SOI Photonic crystal waveguides

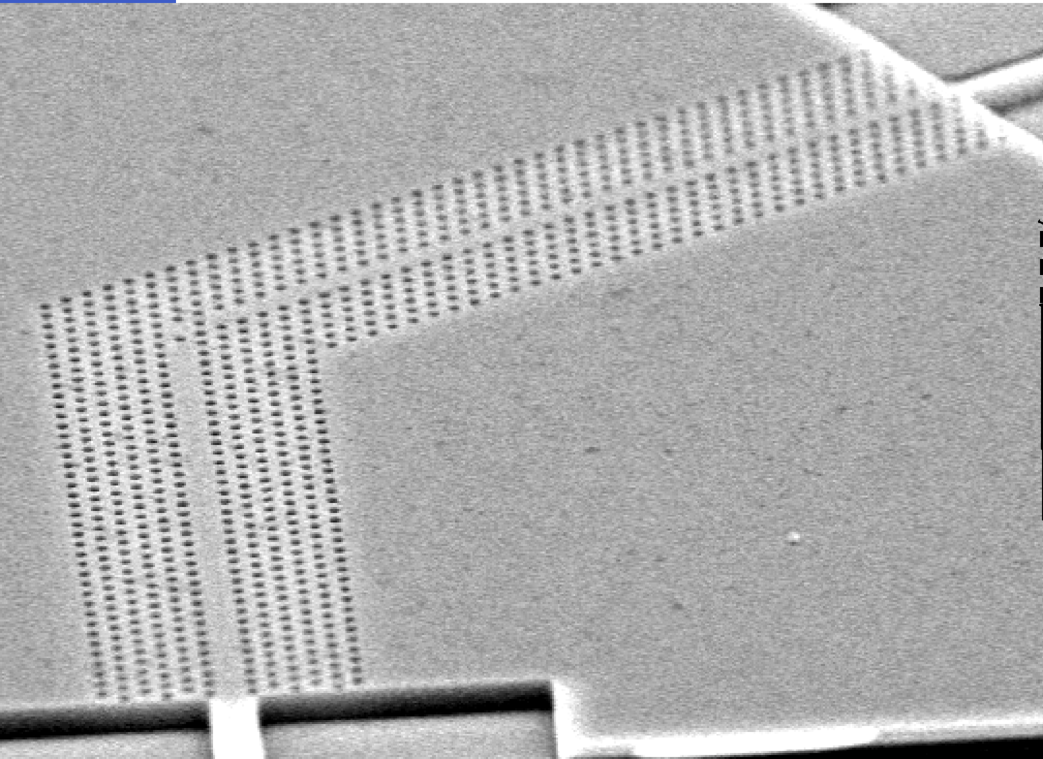
SOI: Good vertical waveguide material

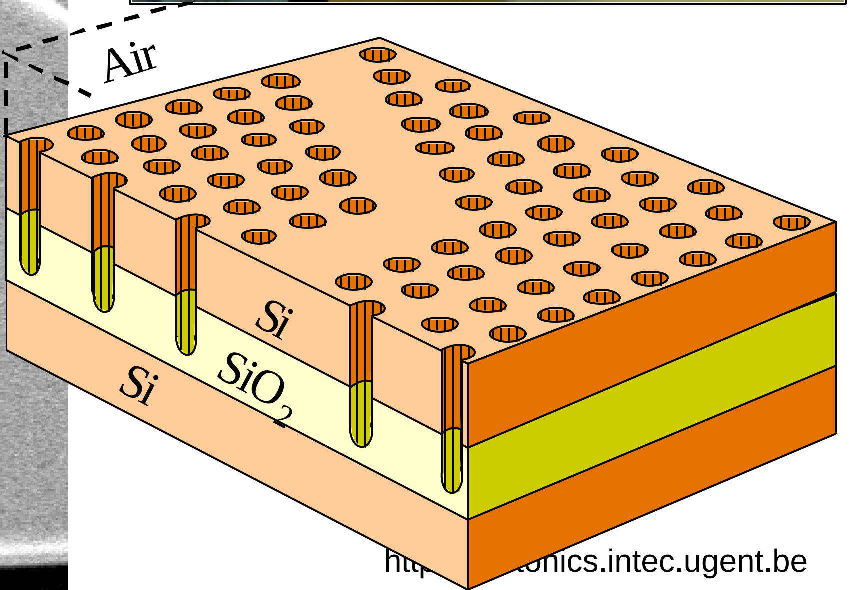
- Top Silicon layer: n = 3.45
- Oxide cladding layer: n=1.45

Fabrication at IMEC

- 248nm deep UV lithography
- Dry etching







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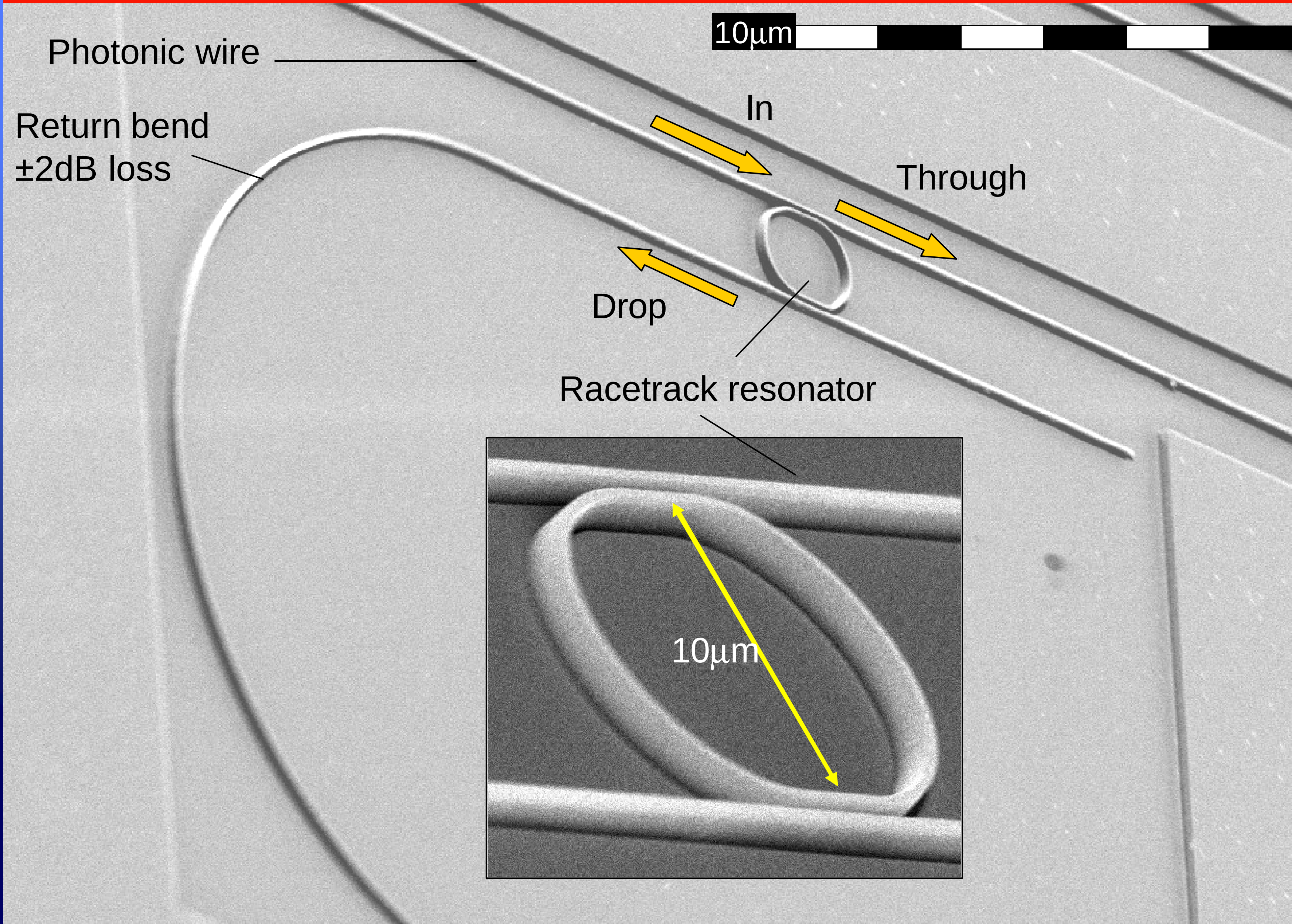
Ring resonators in Silicon on Insulator



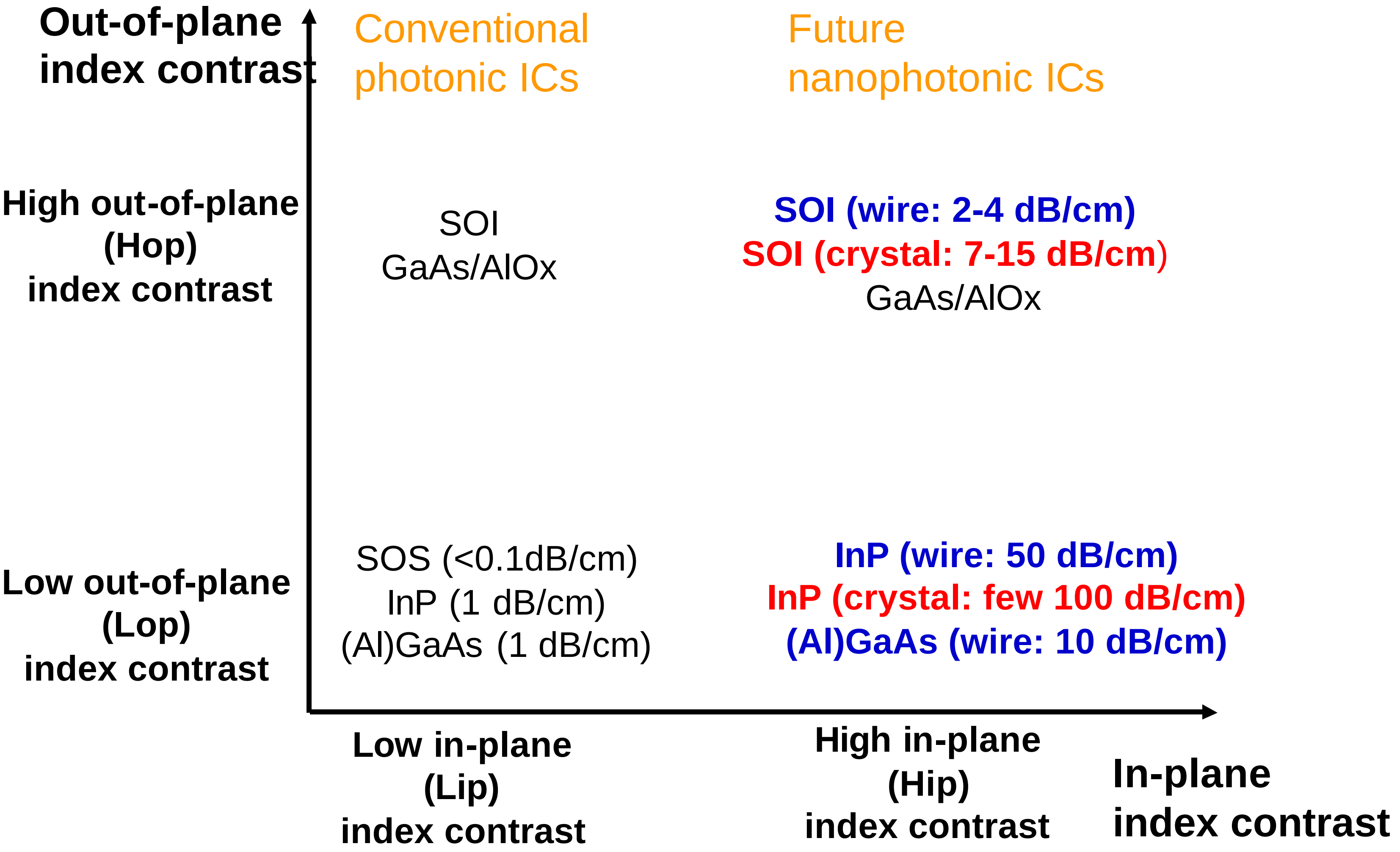
OUTLINE

- Introduction to nano-photonics
- Nano-photonic ICs
- Challenges
  - in the physics
  - in the technology
  - in the packaging

Challenges in the physics

- understand the various loss mechanisms
- high versus low index contrast in the vertical (out-of-plane) direction
- photonic wires versus photonic crystal waveguides
- impact of roughness
- ...

Losses of straight single mode waveguides



Out-of-plane index contrast

Conventional photonic ICs

Future nanophotonic ICs

High out-of-plane (Hop) index contrast

SOI
GaAs/AlOx

SOI (wire: 2-4 dB/cm)
SOI (crystal: 7-15 dB/cm)
GaAs/AlOx

Low out-of-plane (Lop) index contrast

SOS (<0.1dB/cm)
InP (1 dB/cm)
(Al)GaAs (1 dB/cm)

InP (wire: 50 dB/cm)
InP (crystal: few 100 dB/cm)
(Al)GaAs (wire: 10 dB/cm)

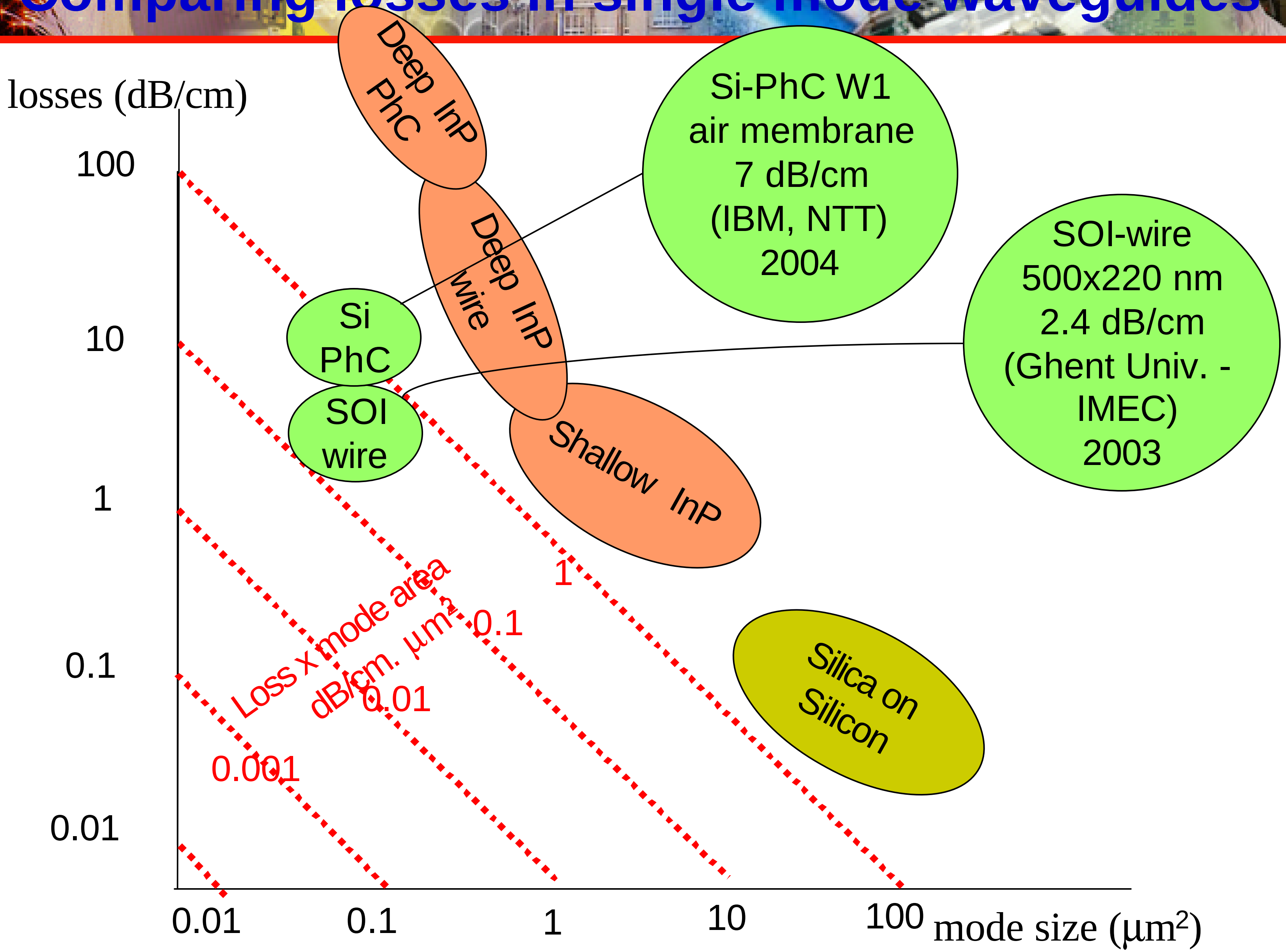
Low in-plane (Lip) index contrast

High in-plane (Hip) index contrast

In-plane index contrast

Best results reported in literature

Comparing losses in single mode waveguides



Si-PhC W1
air membrane
7 dB/cm
(IBM, NTT)
2004

SOI-wire
500x220 nm
2.4 dB/cm
(Ghent Univ. - IMEC)
2003

Losses of straight single mode waveguides

From state-of-the-art experimental results, it seems that:

- **high (out-of-plane) index contrast is an order of magnitude better than low (out-of-plane) index contrast**
- **photonic wire is an order of magnitude better than photonic crystal**

WHY?

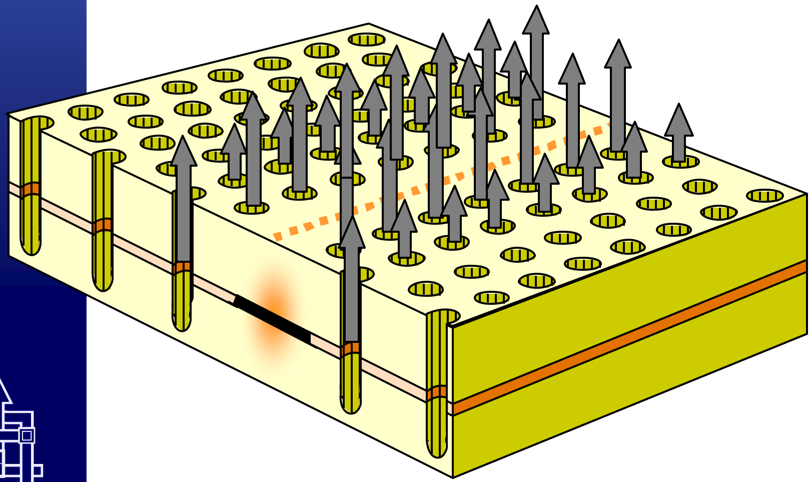
Losses in compact waveguides

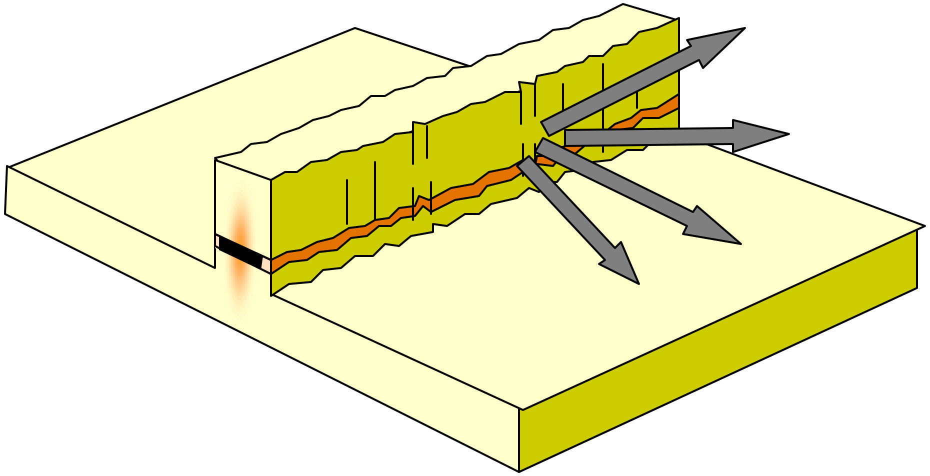
Photonic Crystal

- Perfect in-plane guiding
- Lack of vertical guiding in holes gives out-of-plane scattering losses
- irregularities will add more losses

Photonic Wire

- Perfect guiding in a perfectly made structure
- No PBG to stop the in-plane scattering at irregularities



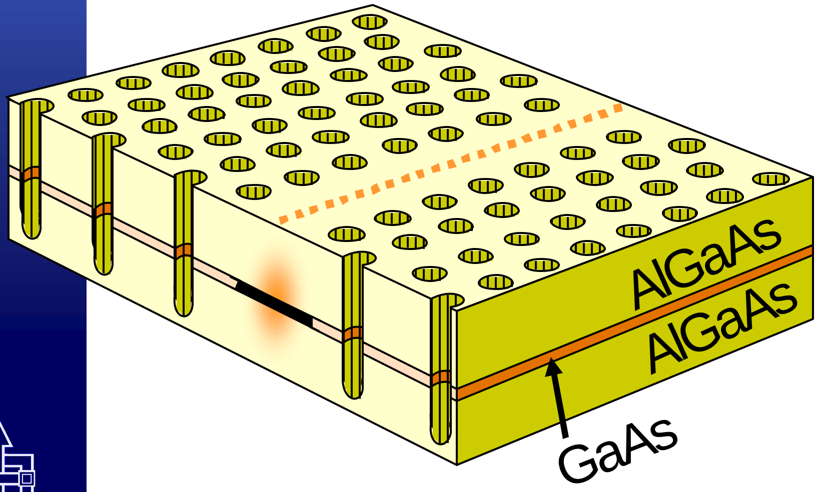


Out-of-plane scattering losses

Question:

To keep out-of-plane scattering low, is it better to have low or high vertical index contrast in your layer structure?

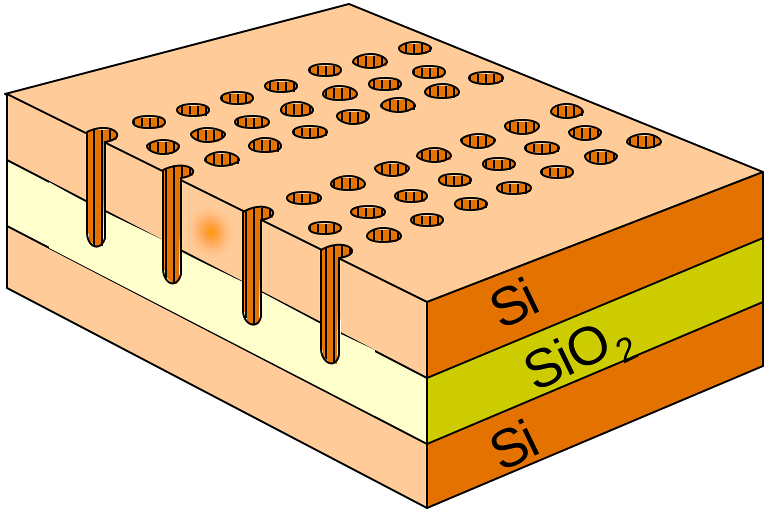
Conventional waveguide
(e.g. GaAs-AlGaAs-structure)



low contrast: 3.5 to 3.2 $(\Delta\varepsilon \approx 2)$

? ↔

Semiconductor ‘membrane’,
Silicon-on-Insulator, GaAs-AlOx

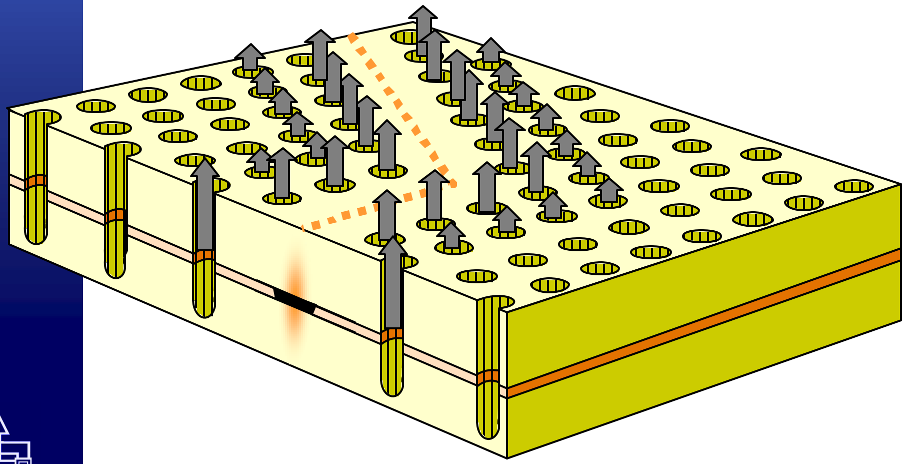


high contrast: 3.5 to 1-1.5 $(\Delta\varepsilon \approx 10)$

High versus low vertical contrast

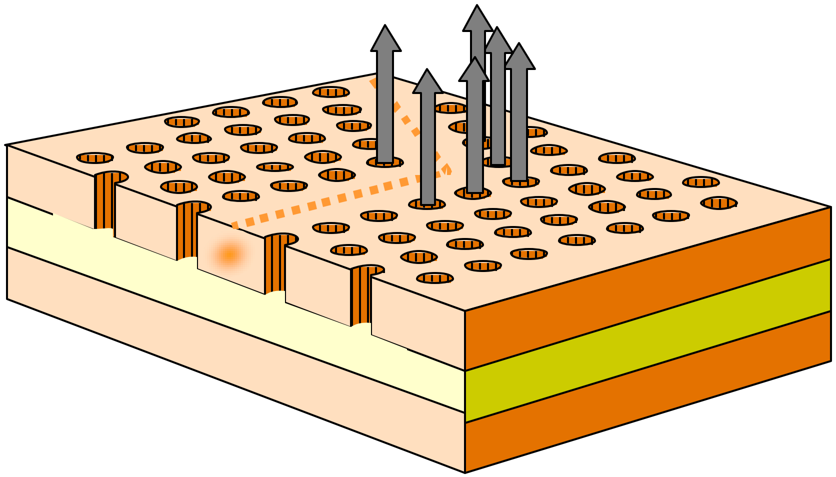
Low refractive index contrast

- Waveguide mode is above the light line
- Losses at discontinuities similar to losses in straight sections

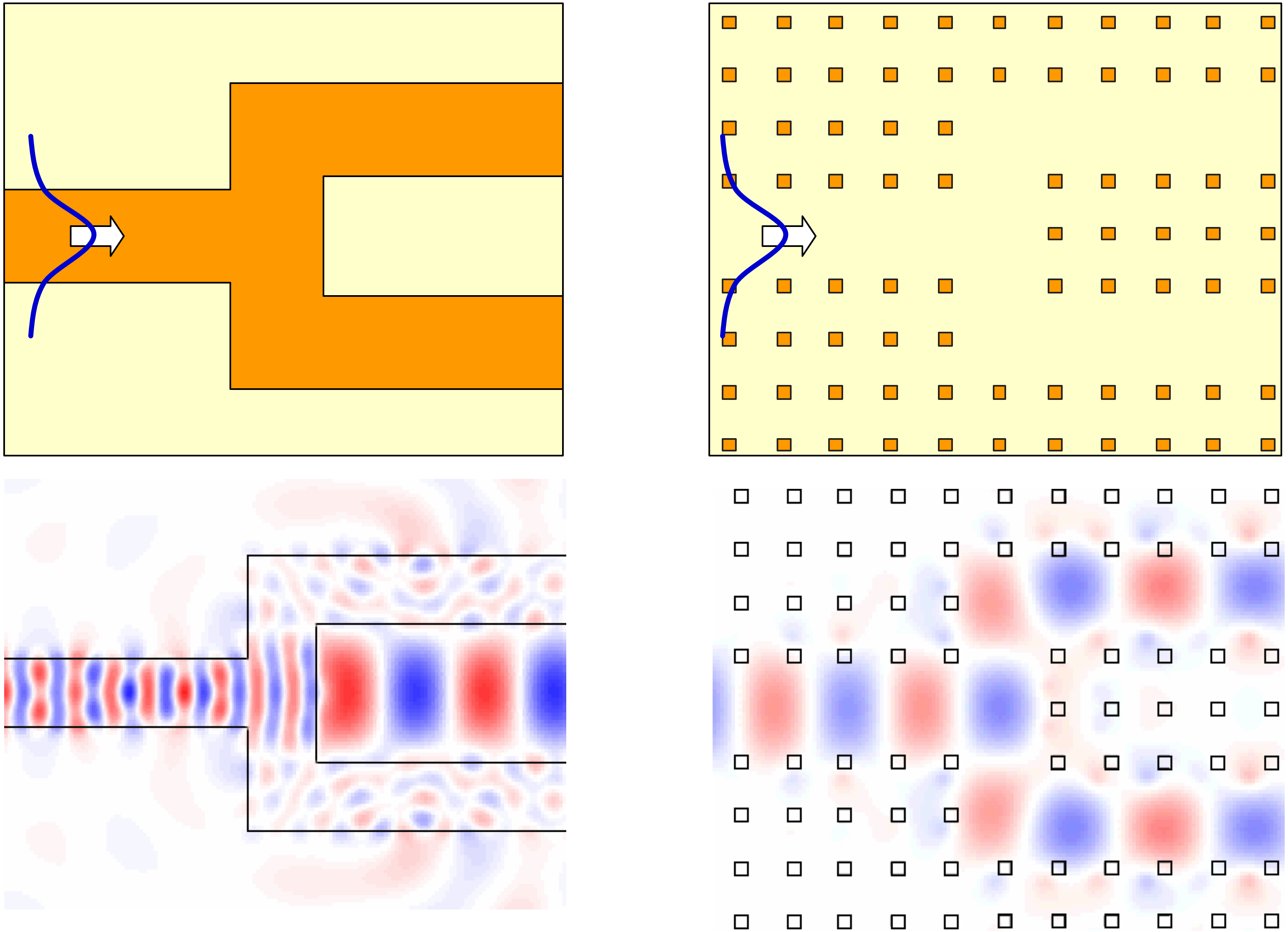


High refractive index contrast

- Guided Bloch mode below the light line and does not scatter
- Discontinuities can scatter massively, unless properly designed



TIR guide versus photonic crystal guide



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Technologies for nano-photonic ICs

NANO-PHOTONIC waveguides
• feature size : 50-500 nm
• required accuracy of features: 1-10 nm (or better)
• large field (at least cm^2)
• alignment to previous patterns: 100 nm accuracy

- **maskless research and prototype technologies**
  - e-beam lithography + reactive ion etching
  - focussed ion beam (FIB) etching
- **mask-based manufacturing technologies**
  - deep UV optical lithography + dry etching
  - nano-imprint lithography (NIL) + dry etching

Nanophotonics by means of CMOS technology

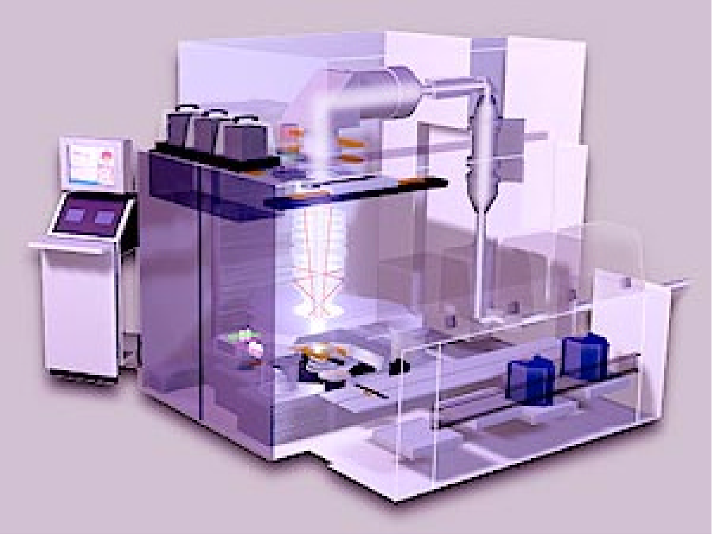
Why?

- Processes with very high performance and reproducibility
- Market for photonic ICs is relatively small: you cannot afford a dedicated fab
- Fabless company model can work

IMEC’s Deep UV Lithography for CMOS

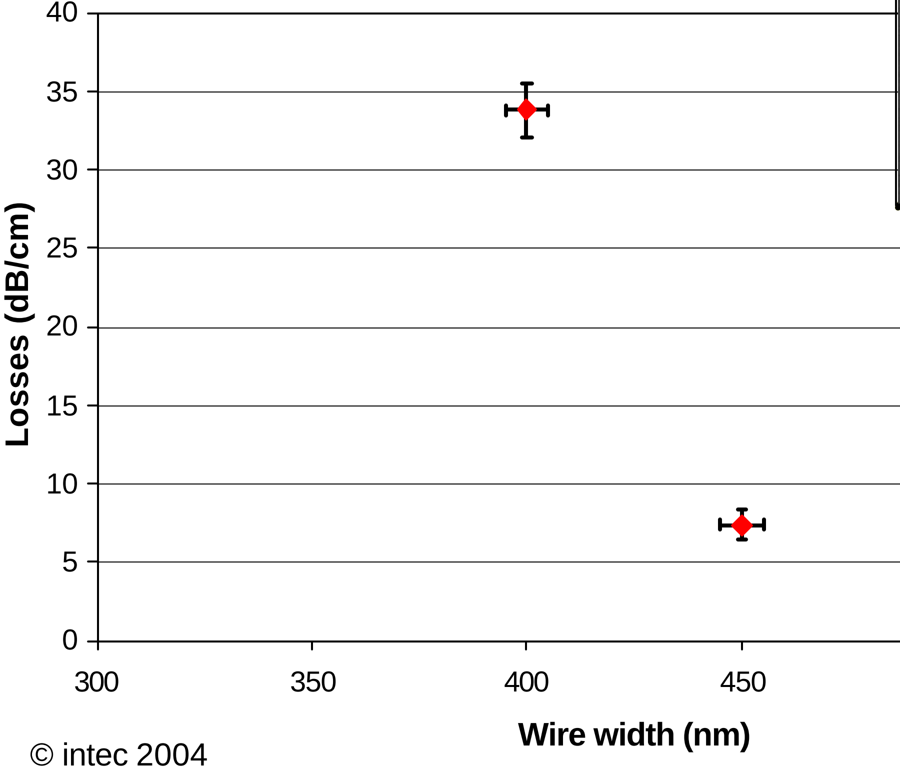
248nm excimer laser Lithography

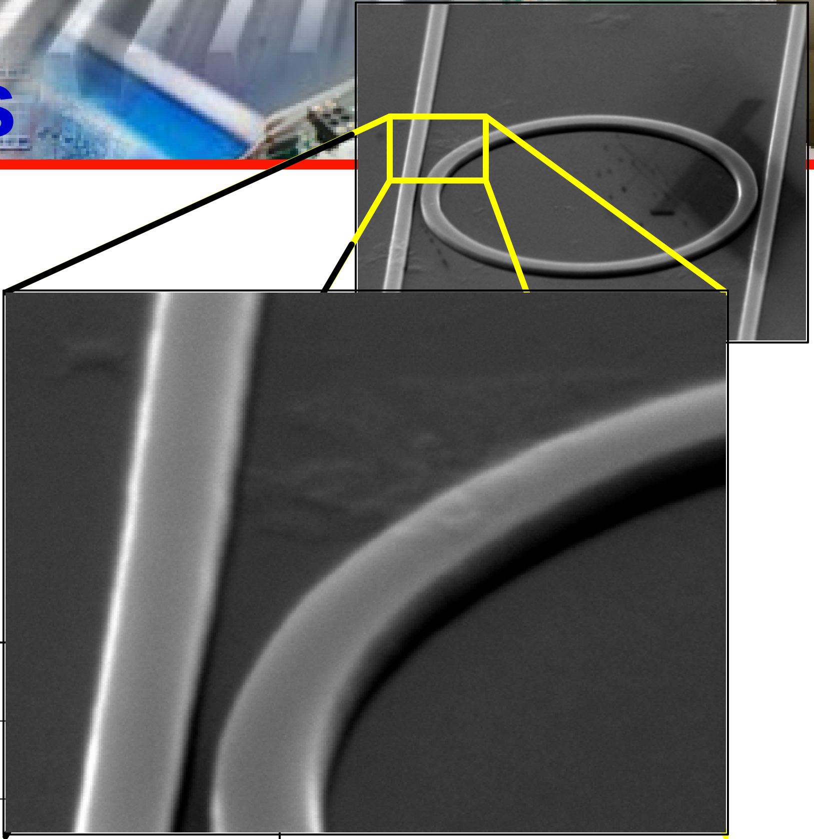
- ASML PAS 5500/300 Stepper and PAS 5500/750 Step-and-scan Stepper
- Automated in-line processing (spin-coating, pre- and post-bake, development)
- 4X reticles
- Standard process

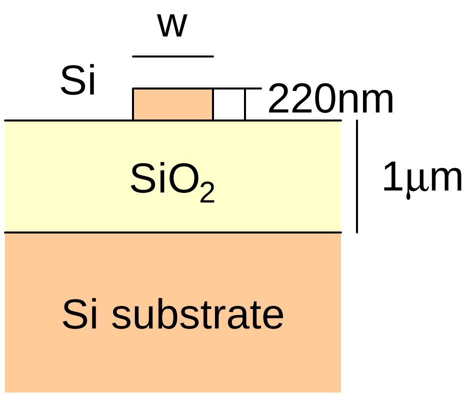


SOI photonic wires

w	Propagation losses
400nm	33.8 ± 1.7 dB/cm
450nm	7.4 ± 0.9 dB/cm
500nm	2.4 ± 1.6 dB/cm







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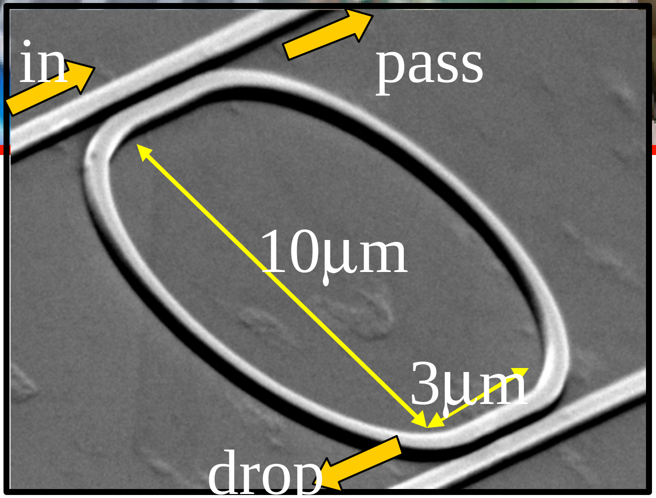
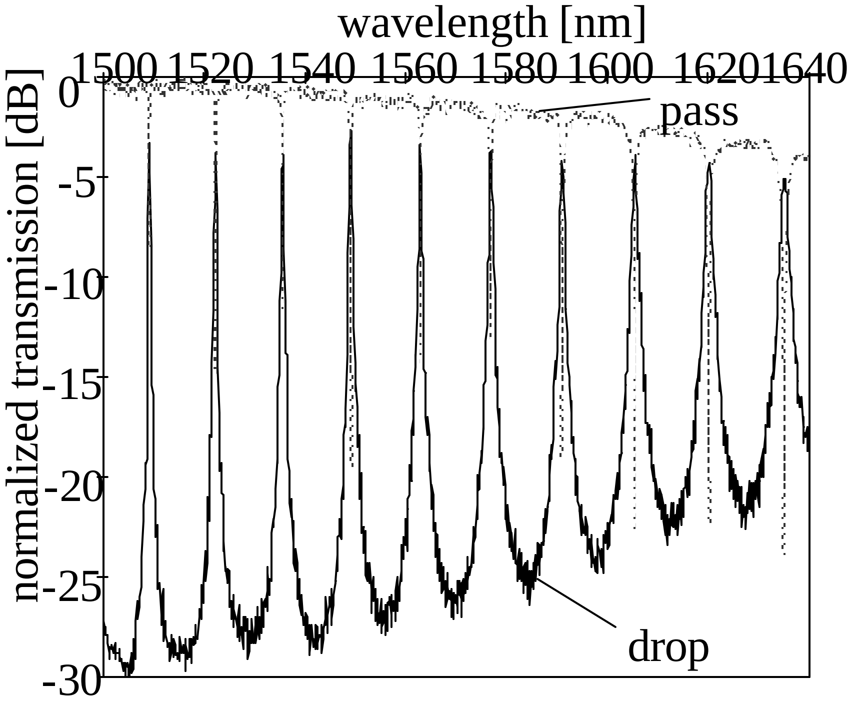
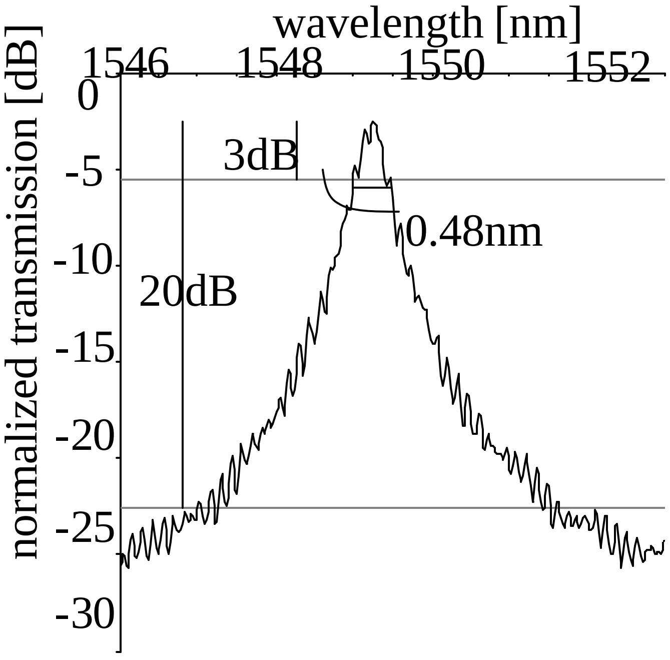
Racetrack resonators

- symmetrically coupled
- wire width = 450nm, gap = 250nm
- k » 0.3 , ring loss » 7.5dB/mm
- finesse 28, Q » 3200

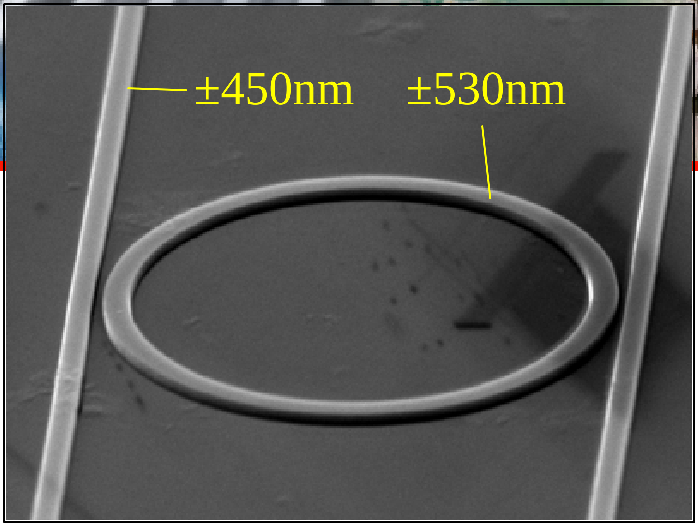


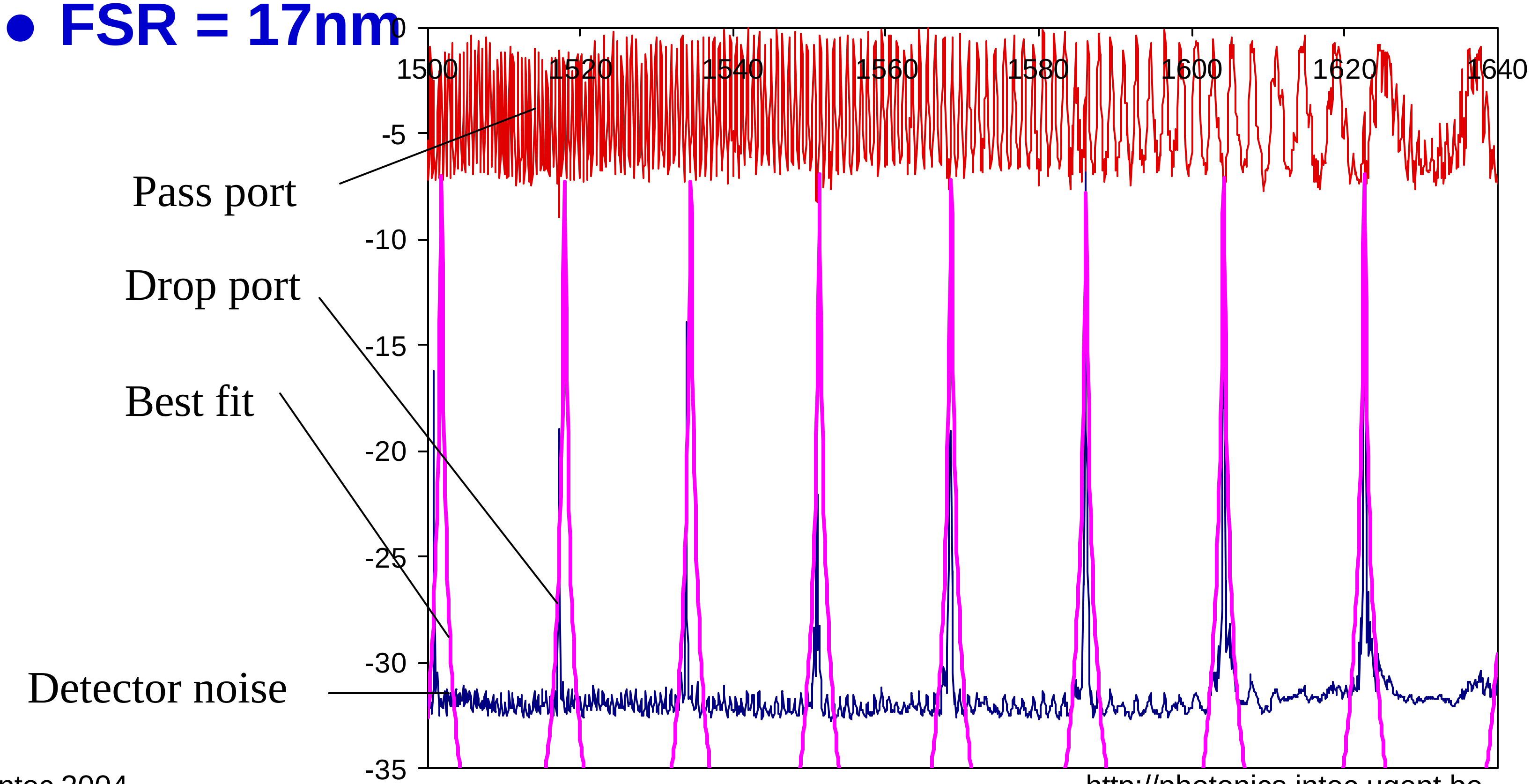




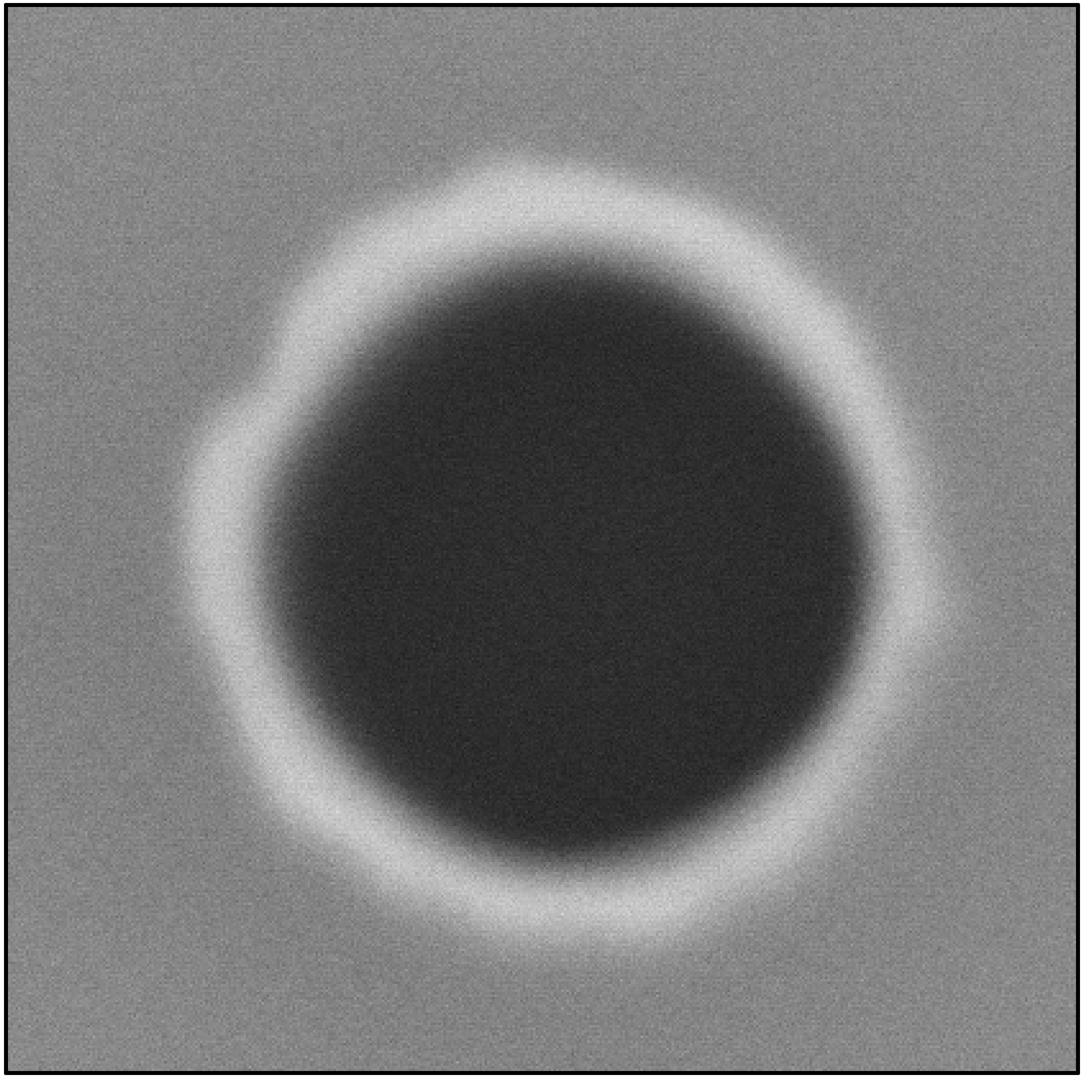
Ring resonator

- Ring radius = 5mm
- TE polarisation
- Q » 8000, Finesse » 88
- FWHM » 0.19nm
- FSR = 17nm





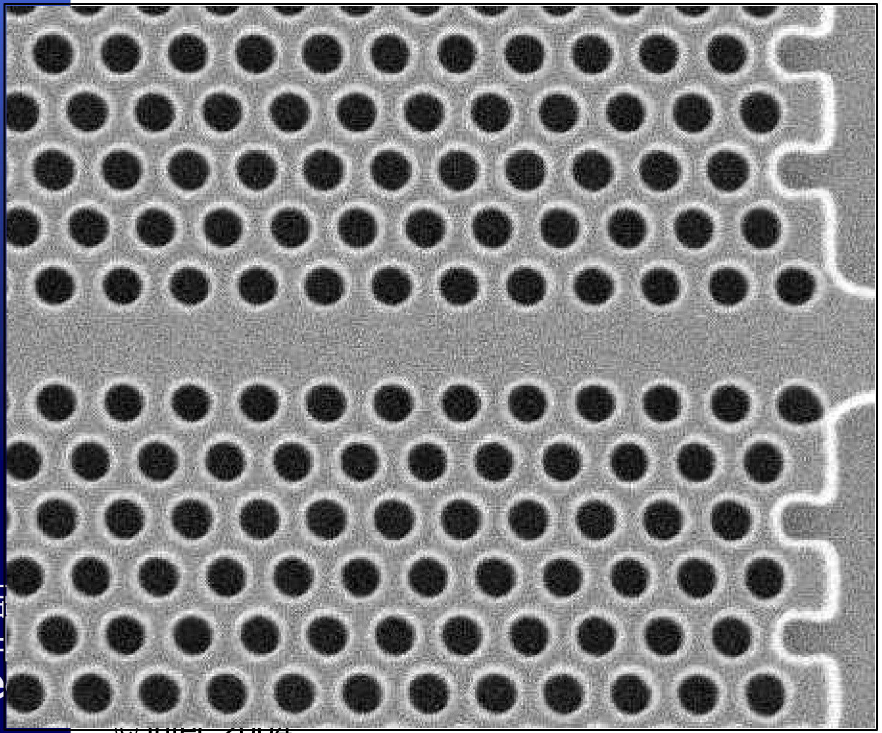
Lots of holes on a 200 mm wafer

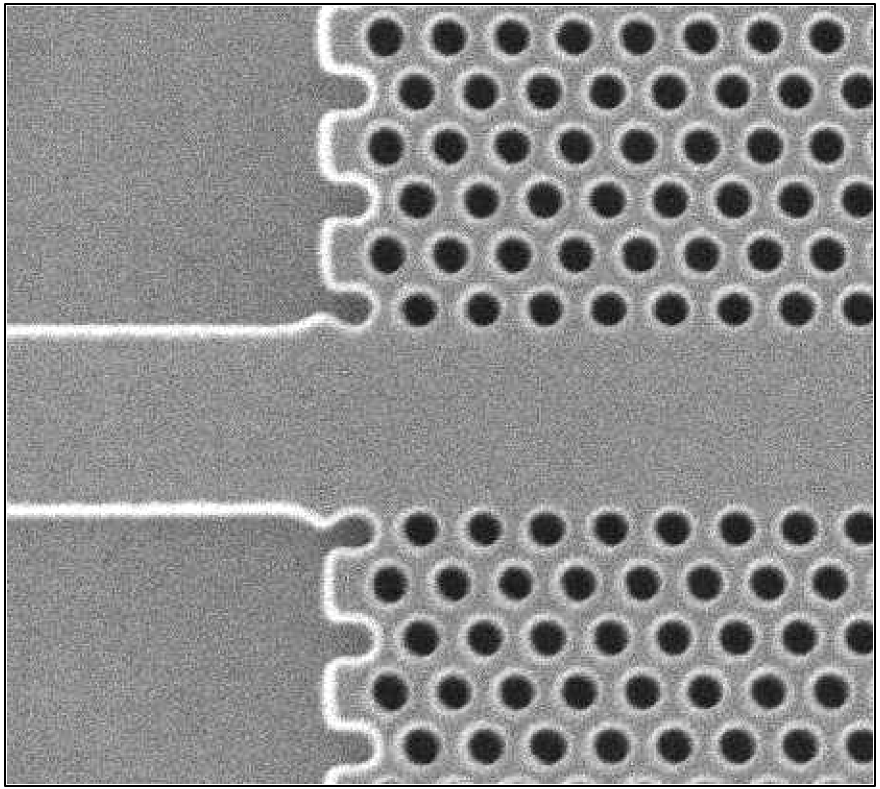


Photonic crystal Waveguides

W1 waveguide

- pitch = 460nm
- hole Ø = 290nm



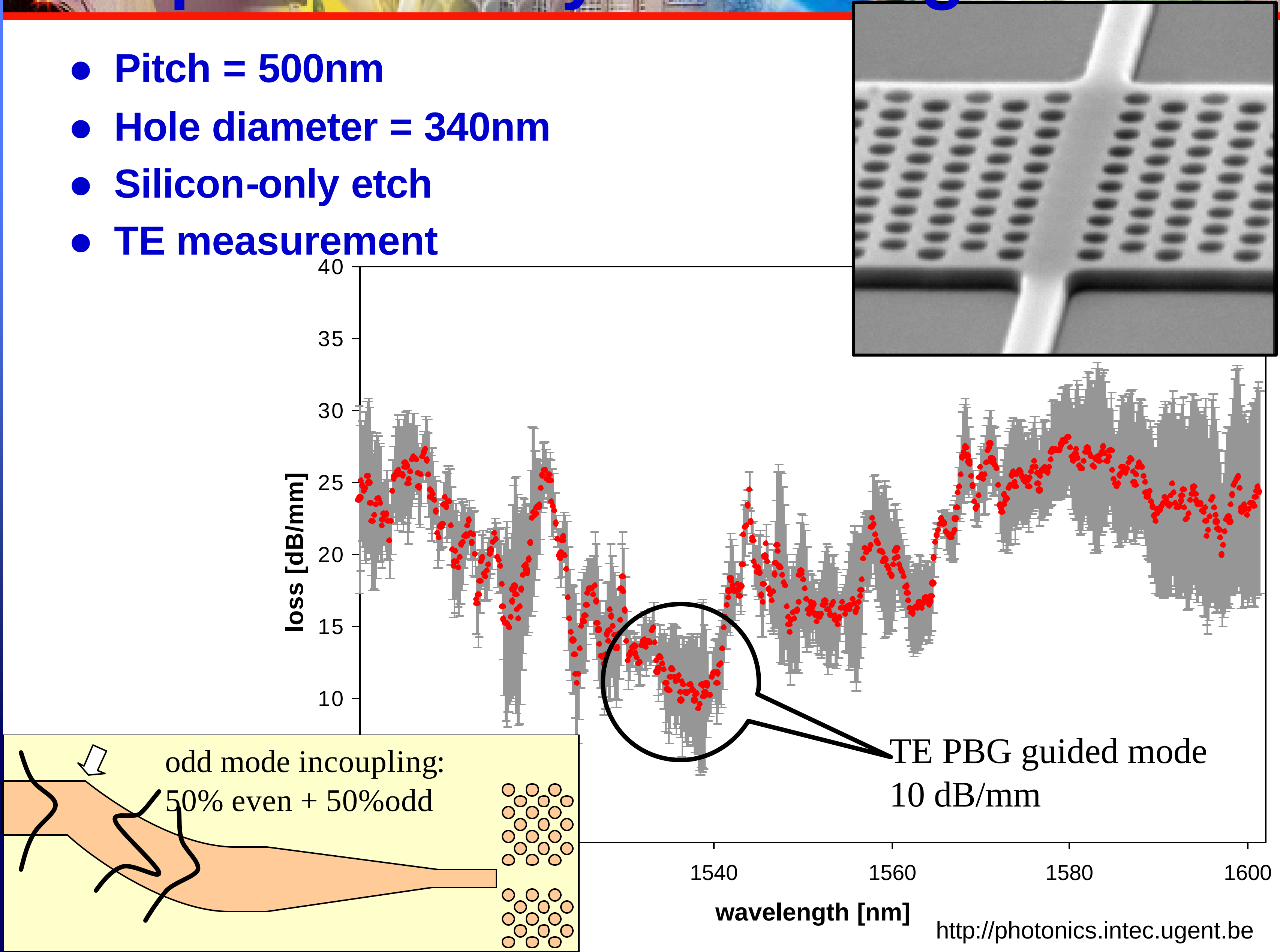


W3 waveguide

- pitch = 460nm
- hole Ø = 290nm

W1 photonic crystal waveguide

- **Pitch = 500nm**
- **Hole diameter = 340nm**
- **Silicon-only etch**
- **TE measurement**



TE PBG guided mode
10 dB/mm

odd mode incoupling:
50% even + 50%odd

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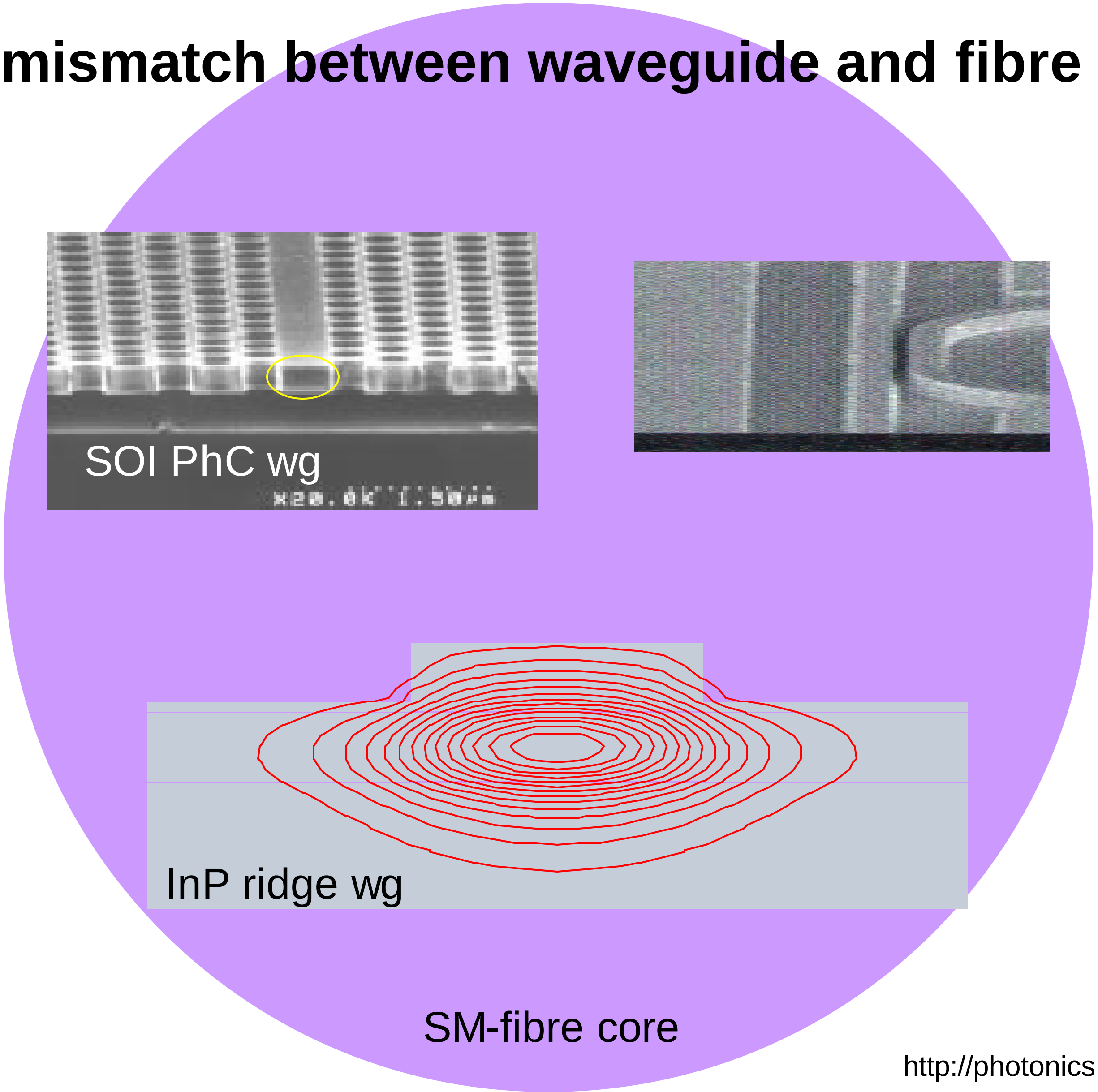
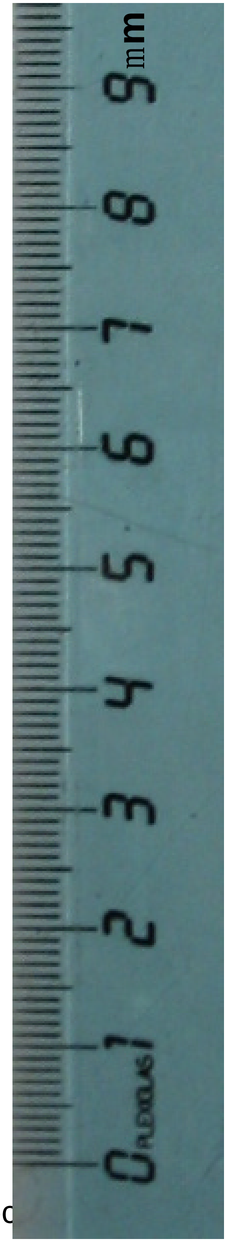
    - in the packaging

Fibre coupling

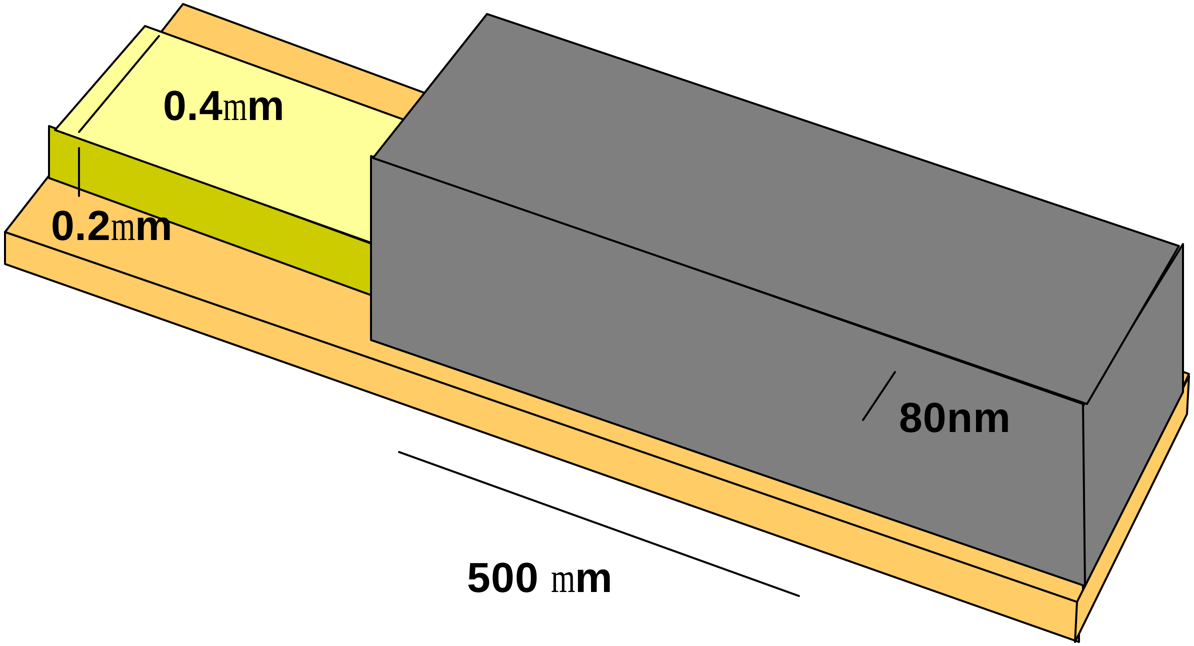
Mode mismatch between waveguide and fibre



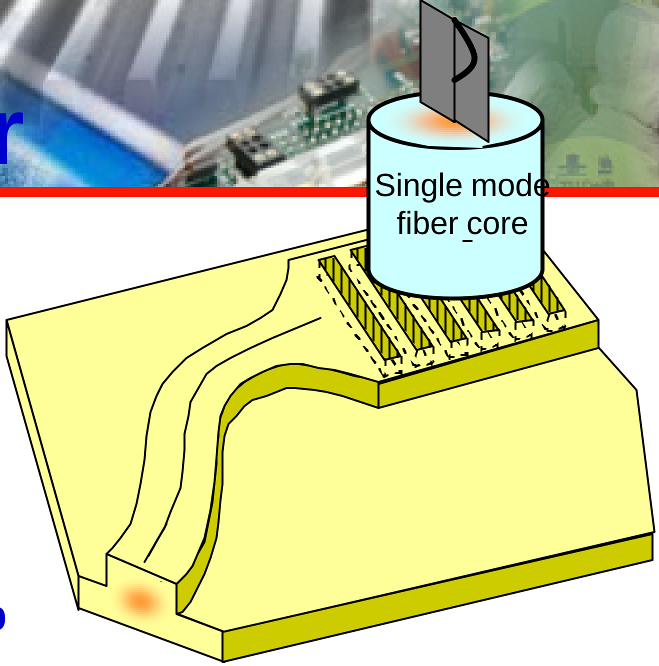


Coupling to fiber

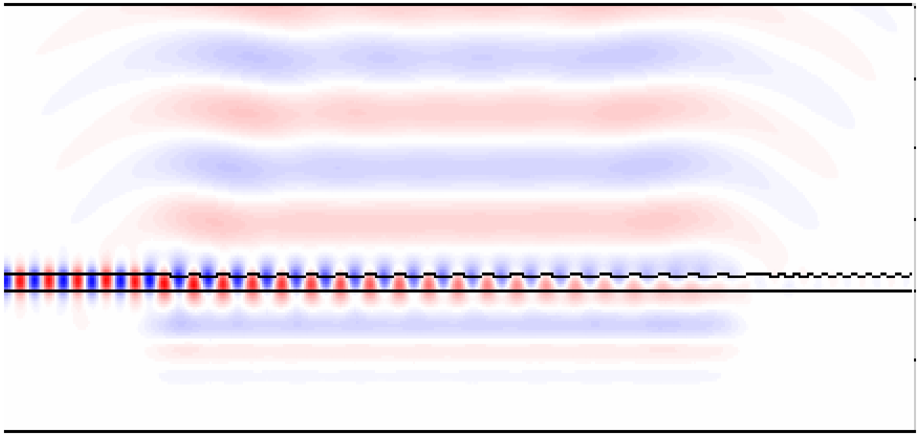
- **polymer on SOI taper (POSOI)**
- **NTT - Notomi**
- **< 0.5dB coupling loss between 0.2mm x 0.4mm waveguide and 4mm Æ fiber**



Surface fiber coupler



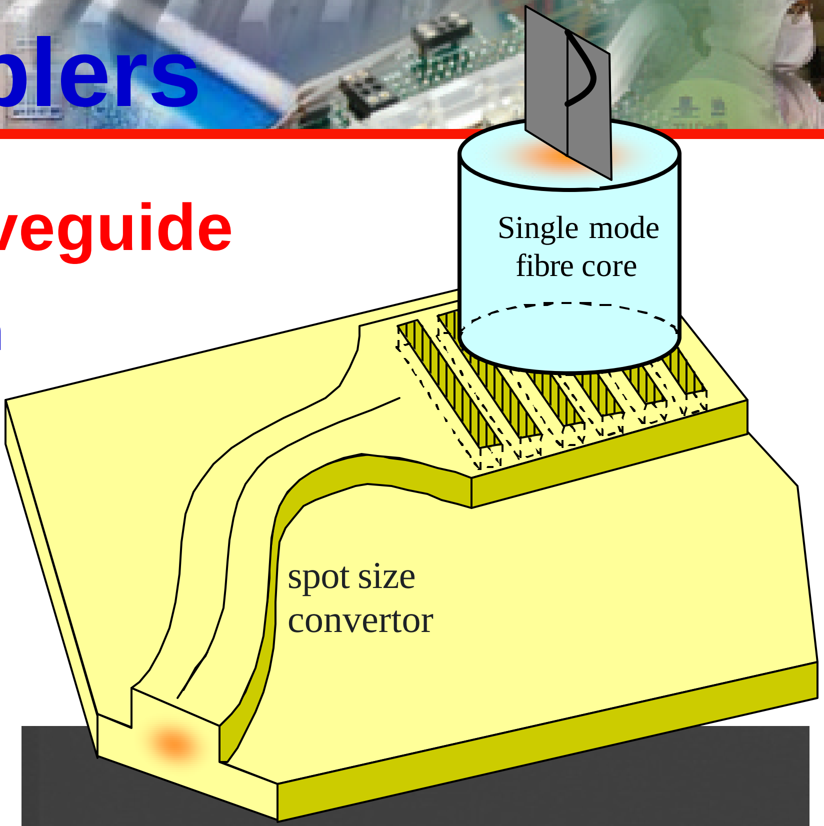
- Coupling by butt coupled fiber
- Coupling area: 10x10 micron
- Allows wafer-level testing
- tolerant alignment
- coupling efficiency (theory): 30-80%
- coupling efficiency to butt-coupled fiber (experim.): 25-33% (Ghent University- IMEC)
- UCLA (CLEO, June 2003): higher efficiency by means of extra layers above grating

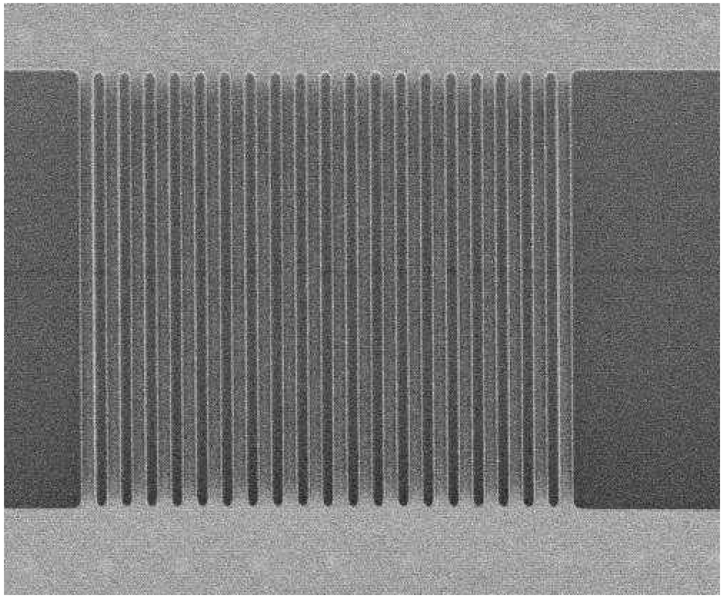


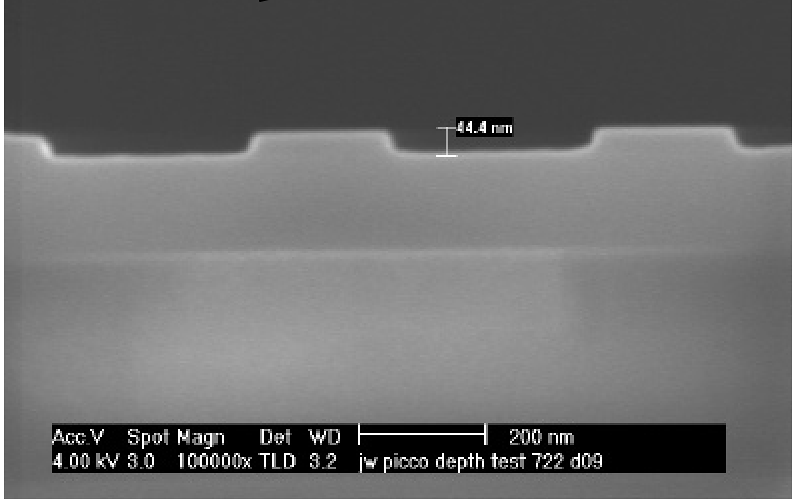
Shallow fibre couplers

Coupling from fibre to waveguide

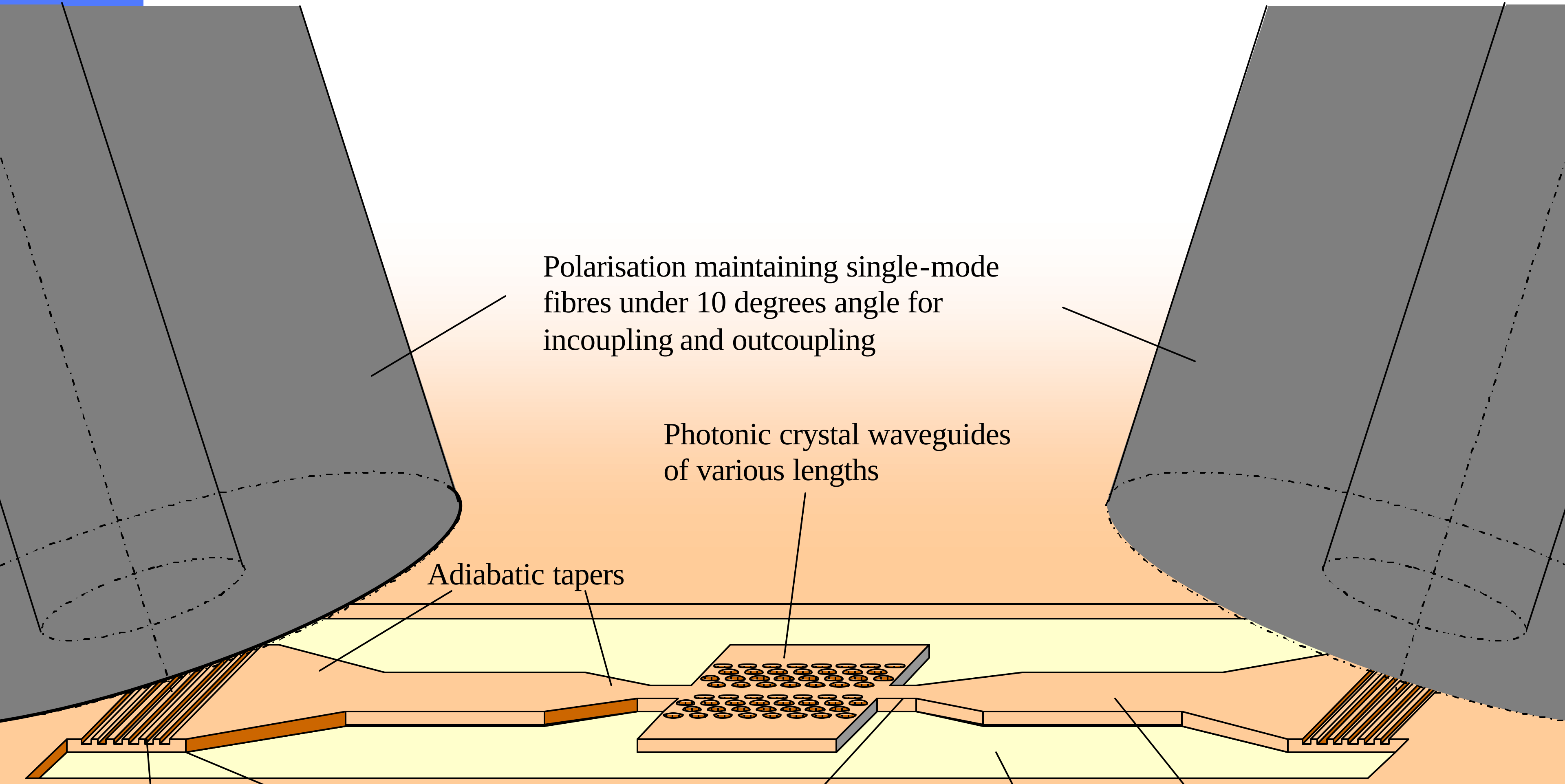
- **Line gratings: period=580nm**
- **Etch depth: 50nm**
- **Very critical features**







Fibre Coupler Measurement setup



Polarisation maintaining single-mode fibres under 10 degrees angle for incoupling and outcoupling

Photonic crystal waveguides of various lengths

Adiabatic tapers

10µm ridge waveguide to match width of fibre mode

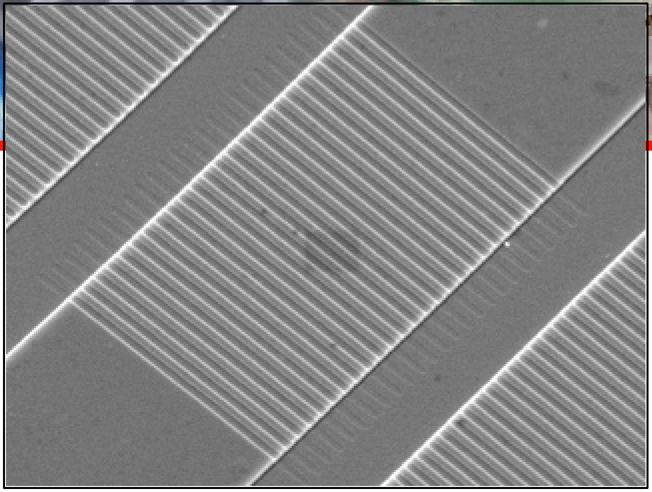
Oxide bottom cladding

Shallow-etched fibre coupler grating for coupling to single-mode fibre

500nm wide Photonic wire for coupling to photonic crystal

3µm ridge waveguide for optional cleaving for end-fire incoupling and/or outcoupling

Fibre couplers

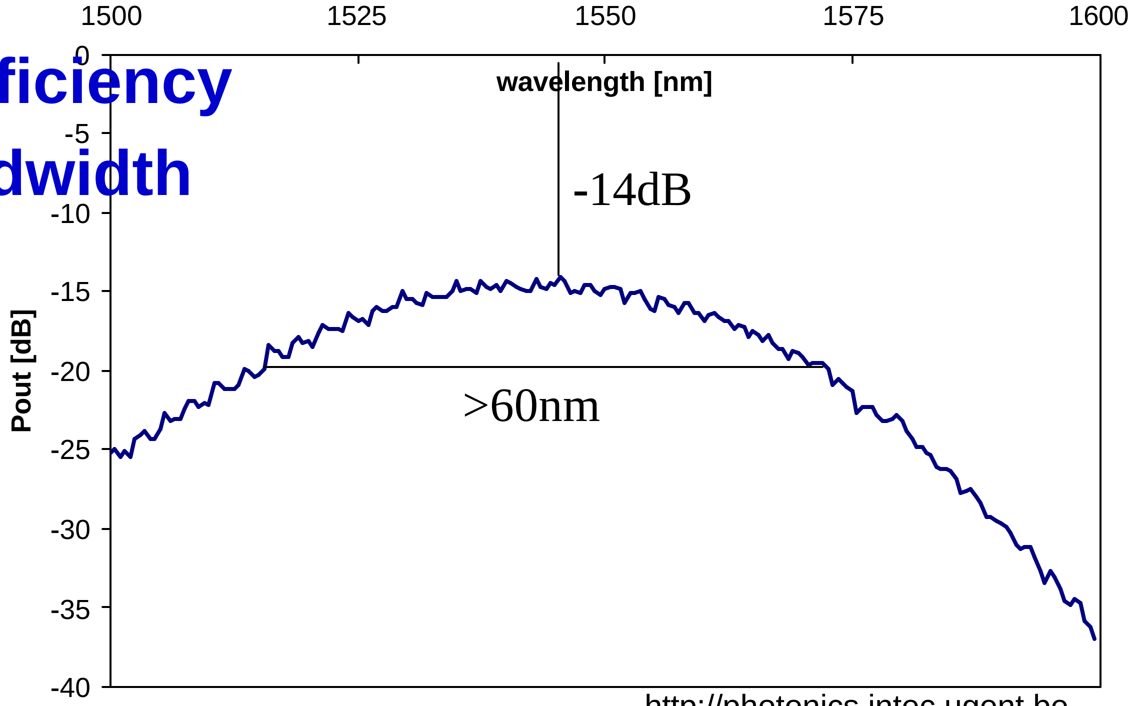


Fibre to fibre:

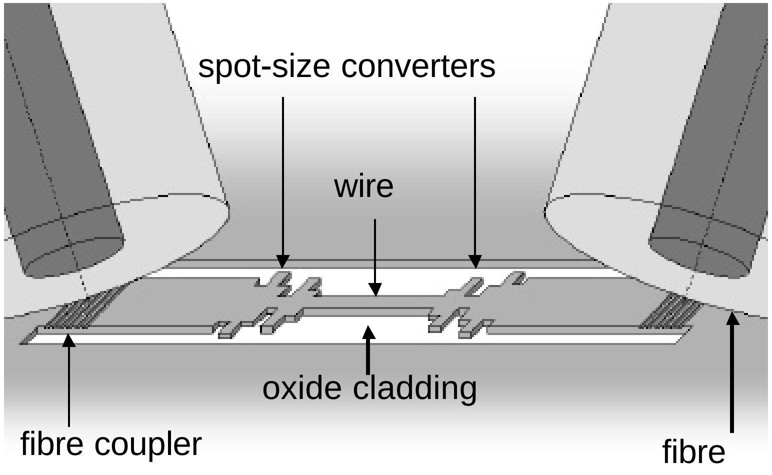
- -14 dB maximum transmission
- 60nm 6dB bandwidth

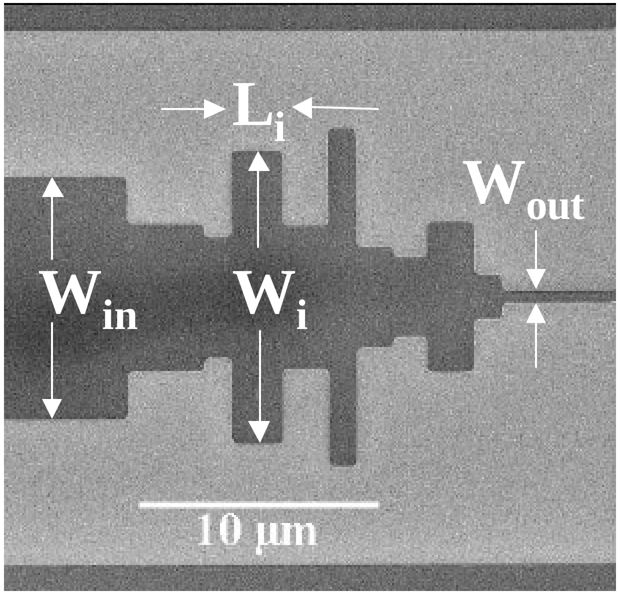
Per coupler:

- -7dB ® 20% efficiency
- 60nm 3dB bandwidth



Interferometric couplers



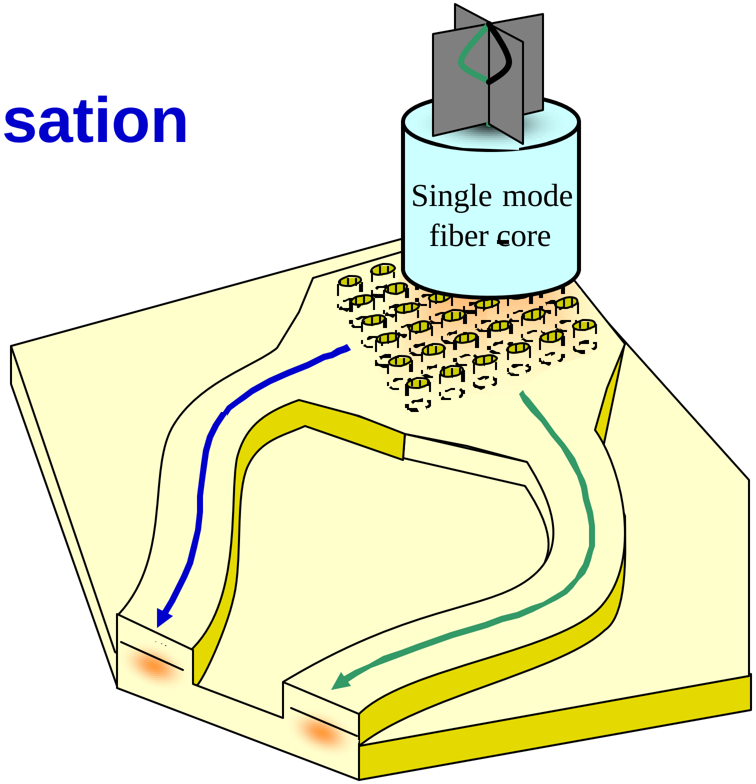


- **much shorter than adiabatic tapers**
- **optimized by means of genetic algorithms**
- **best experimental result: 70% transmission (for width = 10 mm to 0.5 mm, length = 15 mm)**

2D grating fiber coupler

Fiber to waveguide interface for polarisation independent photonic integrated circuit

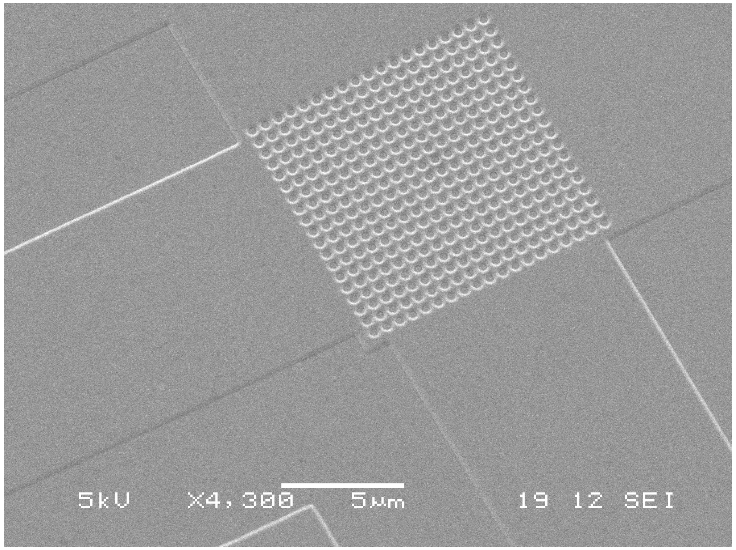
- 2D grating
- couples each fiber polarisation in its own waveguide
- in the waveguides the polarisation is the same (TE)
- Allows for <u>polarisation diversity</u> approach

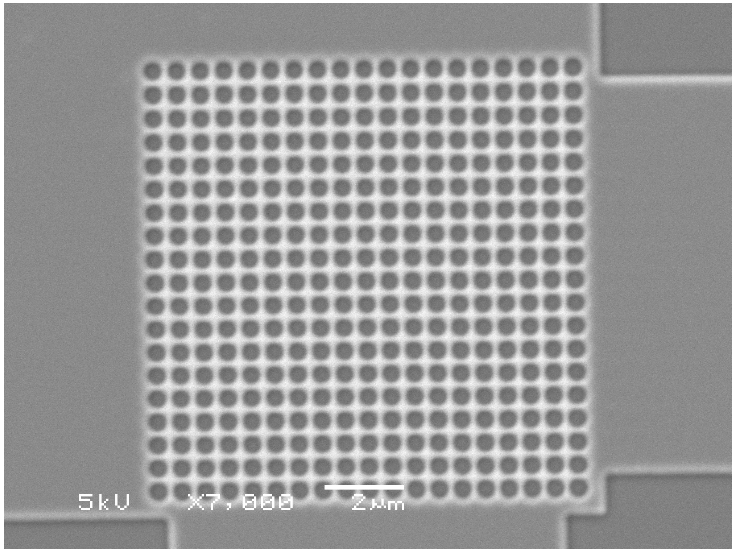


Experimental results

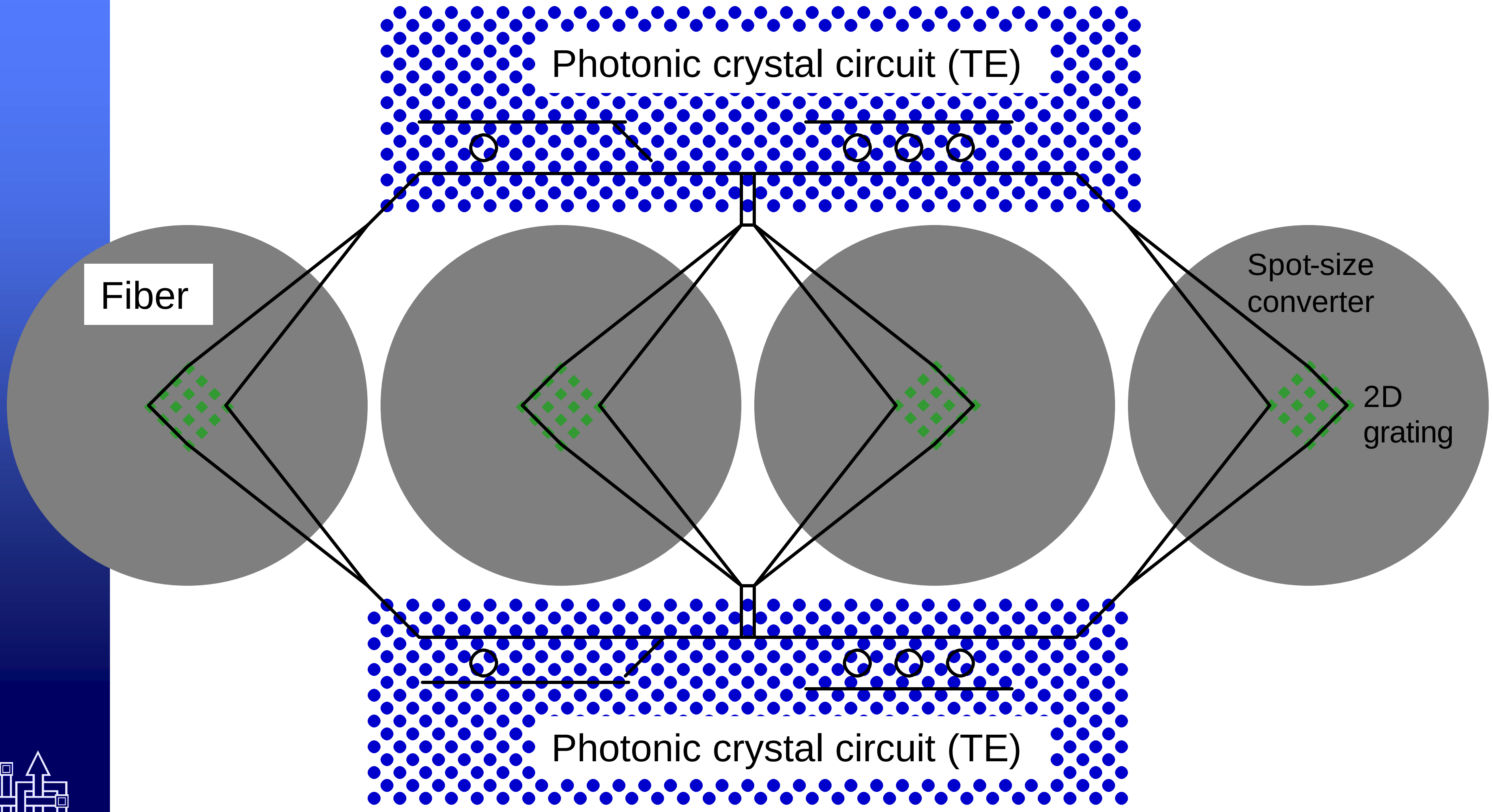
Fabrication

- SOI: 220nm Si / 1000nm SiO_2
- Etch depth: 90nm
- Square lattice of holes: 580nm period





Polarization splitter application



Photonic crystal circuit (TE)

Fiber

Spot-size converter

2D grating

Photonic crystal circuit (TE)

Conclusions

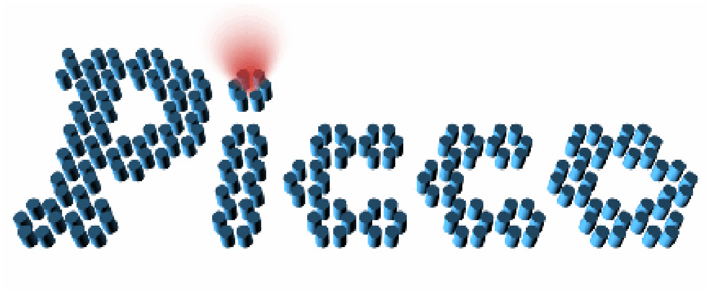
- Nano-photonic ICs based upon wavelength scale high index contrast structures have a huge potential and can bring LSI-level integration into the world of photonics.

- The understanding of the physics and the required technologies are all making rapid progress.

- Nano-photonic ICs can take advantage of the nanostructuring technologies developed for next-generation micro-electronics.

Acknowledgements

- the European PICCO project



http://photonics.intec.ugent.be/picco

- the SPT-division at IMEC
- the photonics group at Ghent University-IMEC