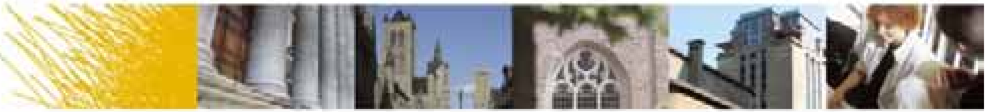


nanophotonics in silicon-on-insulator

Wim Bogaerts

IMEC, 9 June 2006

“the art of playing with light in all its forms”

nanophotonics in silicon-on-insulator

Wim Bogaerts

IMEC, 9 June 2006

“a trendy prefix indicating the need for nanometer-scale accuracy”

“a wafer of silicon buttered with a slice of oxide (insulator) and a delicious layer of silicon”

Photonics Research Group

- research group of Ghent University
- within Engineering Faculty
- within Dept. of Information Technology (INTEC)
- associated with IMEC
- permanent staff:
  Roel Baets, Peter Bienstman, Geert Morthier,
  Dries Van Thourhout, Steven Verstuyft
- 30-35 researchers (7 post-docs)
- research domains: microphotonics and nanophotonics
- http://photonics.intec.ugent.be

Silicon Photonics and UGent-IMEC

UGent – INTEC: Photonics Research Group

- 3 decades of photonics research
- Cleanroom facilities for III-V processing
- Photonics modelling
- Characterisation
- Associated Lab of IMEC

6 years of collaboration on Silicon Photonics

IMEC:

- Microelectronics Research
- Advanced Silicon Processing
- “Nanoelectronics”

Overview of this presentation

Background on Photonics

- What’s the use?
- How does a waveguide work?
- Photonic Crystals
- SOI Nanophotonics

UGent - UGent - IMEC achievements

- What can we do now?
- Some key results

Worldwide State-of-the-art

Conclusion

Overview of this presentation

Background on Photonics

- What's the use?
- How does a waveguide work?

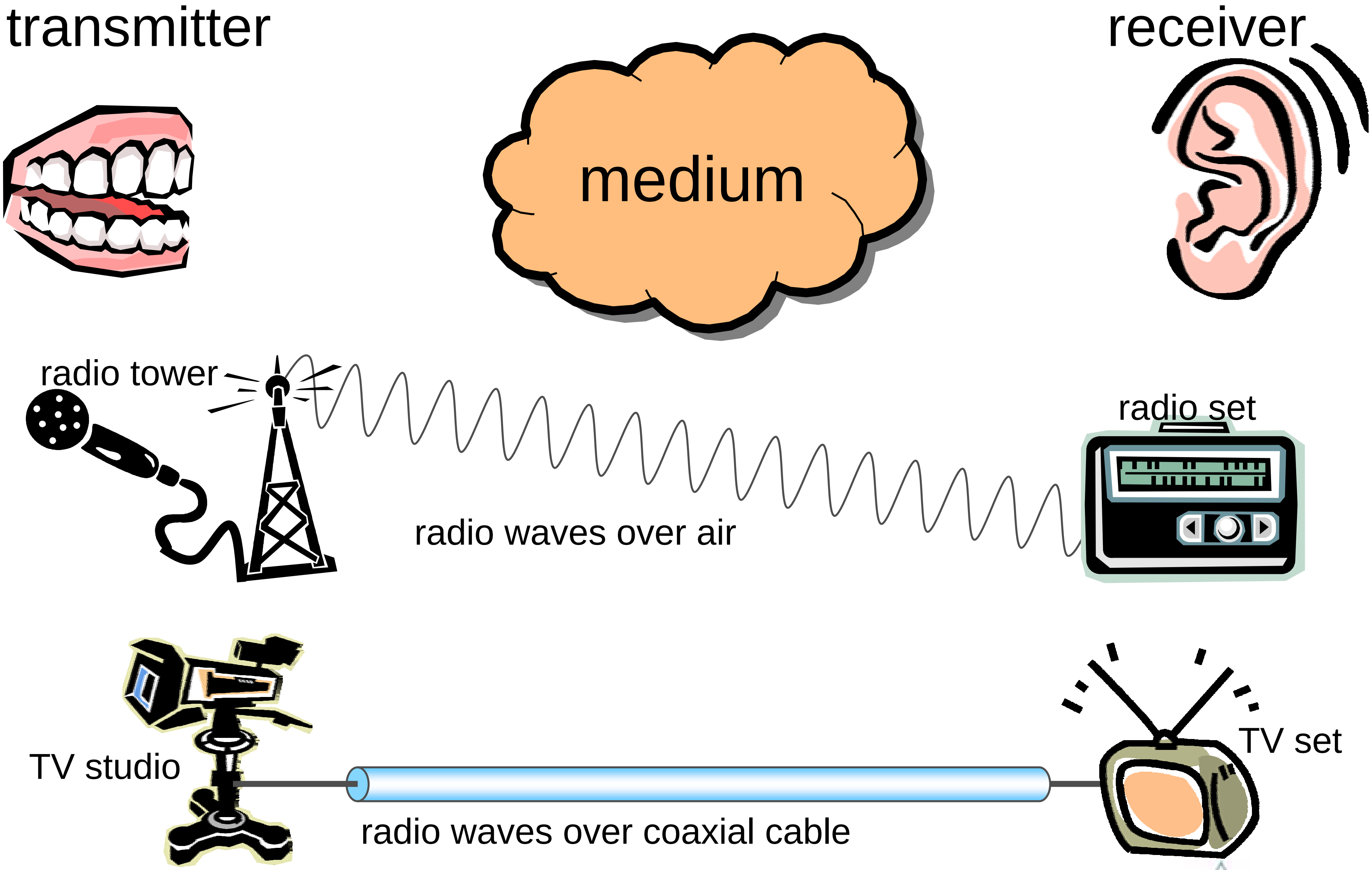
What will we use photonics for?

UGent - IMEC achievements

Long-haul Telecom and FTTH
Datacom (chip, board, metro)
Sensors & spectroscopy

Conclusion

Telecommunication



transmitter

medium

receiver

radio tower

radio waves over air

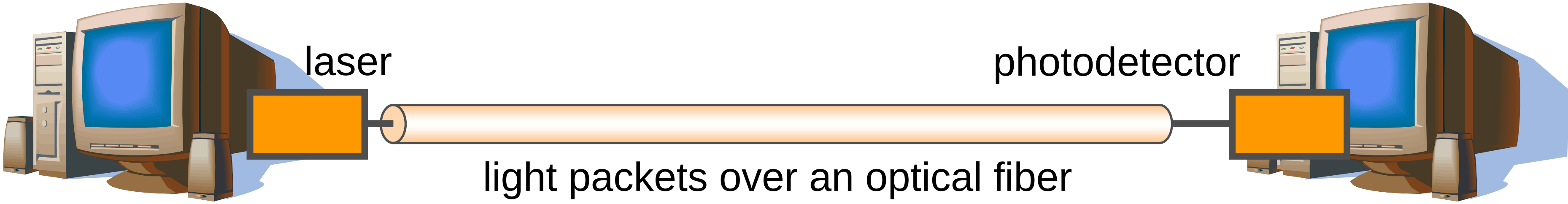
radio set

TV studio

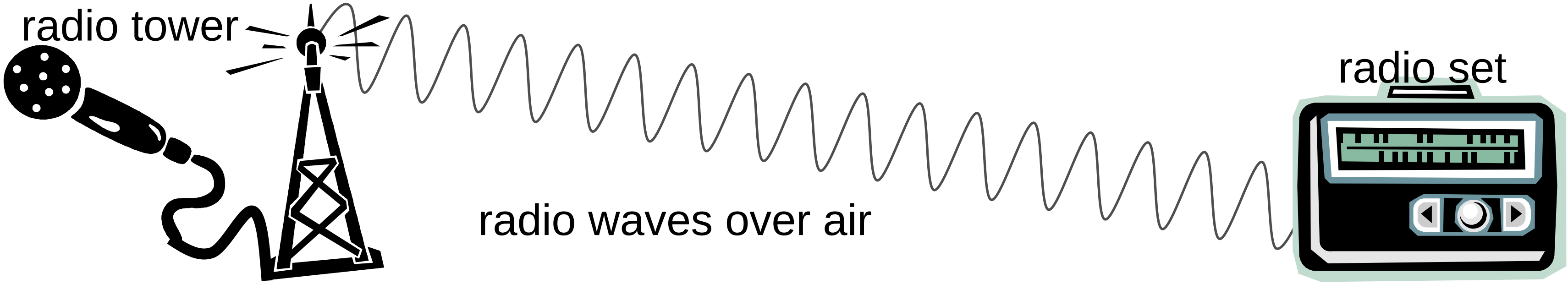
radio waves over coaxial cable

TV set

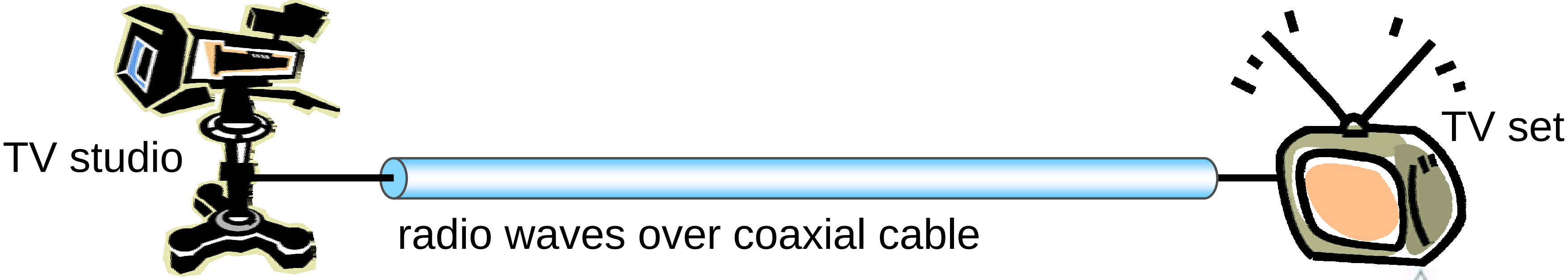
Telecommunication



light packets over an optical fiber
(= electromagnetic wave)

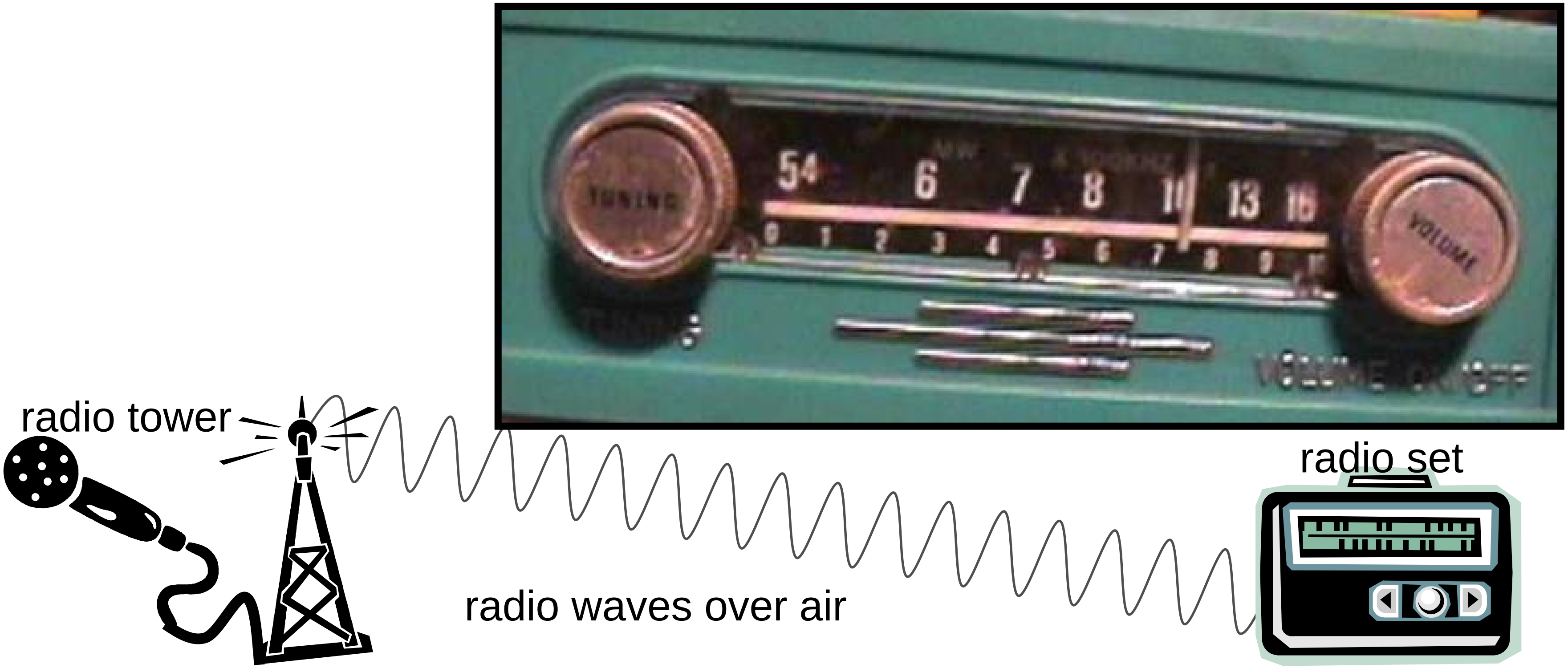


radio waves over air



radio waves over coaxial cable

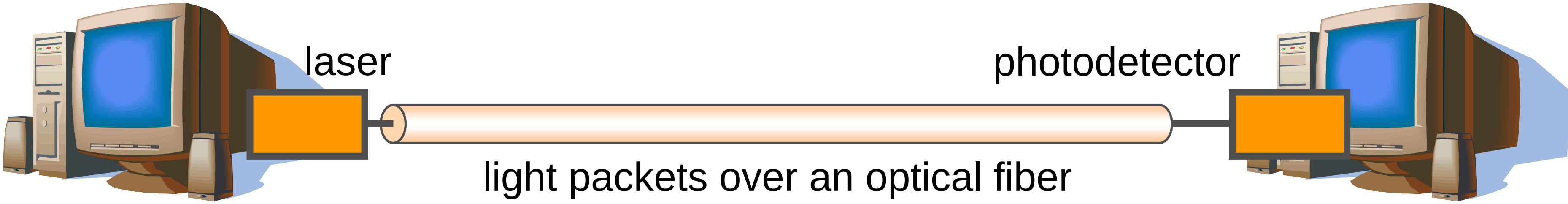
Frequency Division Multiplexing



Transmission of signal on carrier wave

- Carrier wave has a frequency/wavelength
- All carriers travel independent over medium
- Receiver can tune in on one carrier

Wavelength Division Multiplexing



light packets over an optical fiber
(= electromagnetic wave)

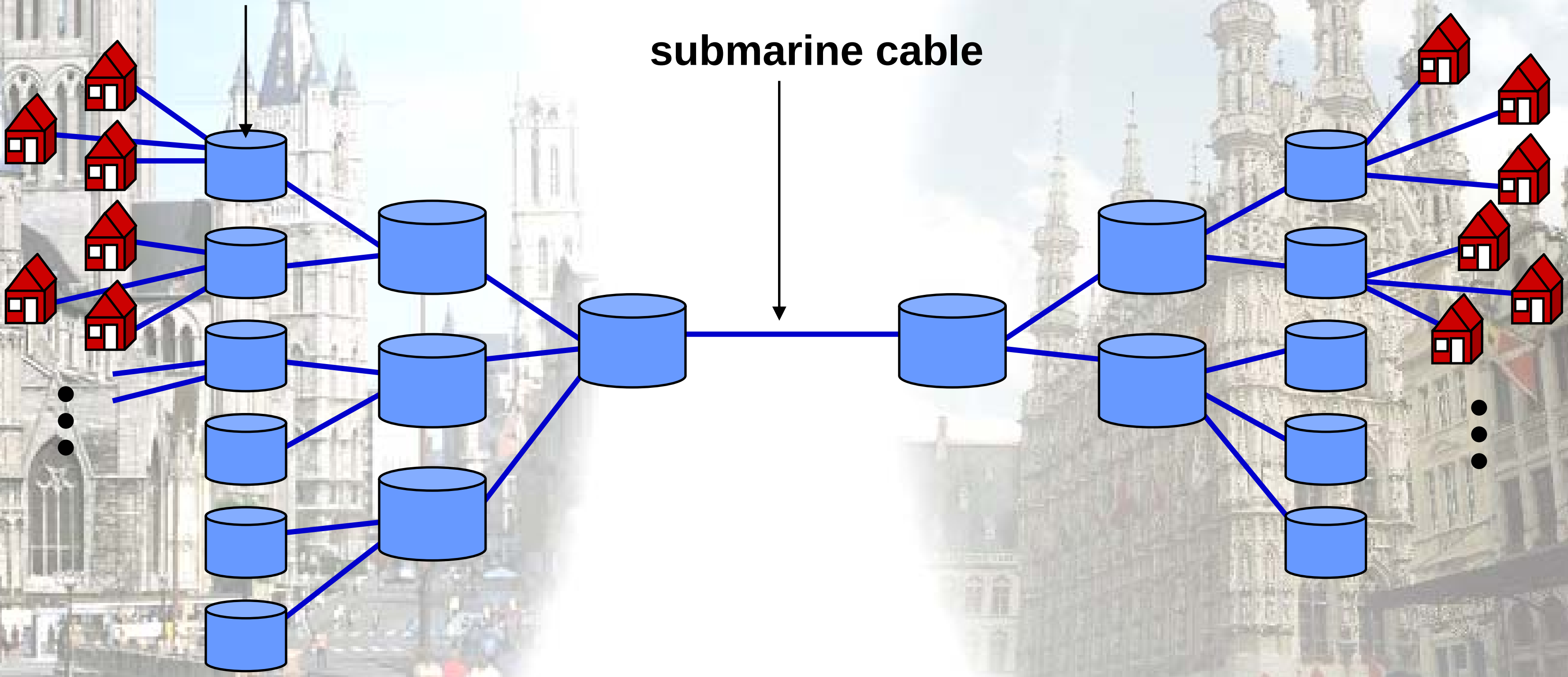
- Use light of different wavelengths (‘colors’)
- Modulate each carrier independently
- combine/split carriers at the end of fibers

LONG DISTANCE
LARGE BANDWIDTH

Where to use optical fibres?

Worldwide telecom

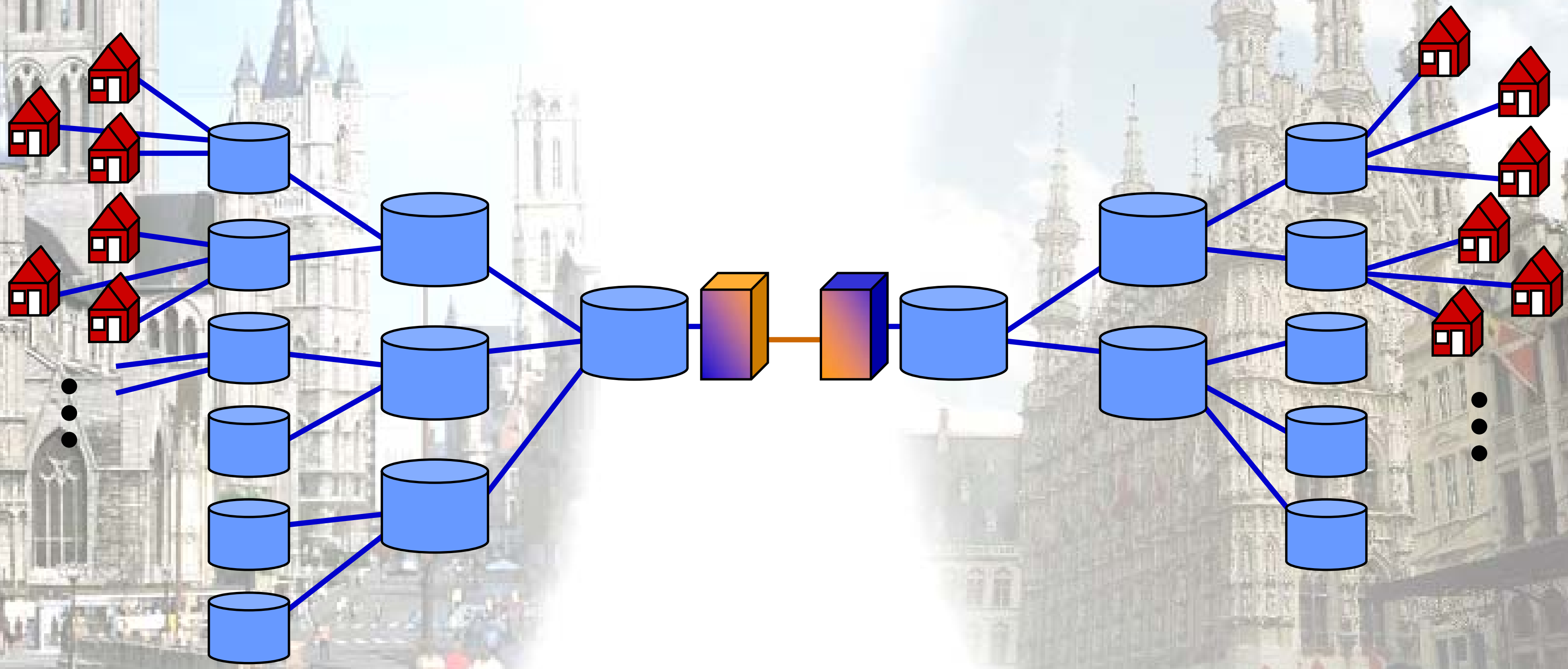
Telecommunication networks



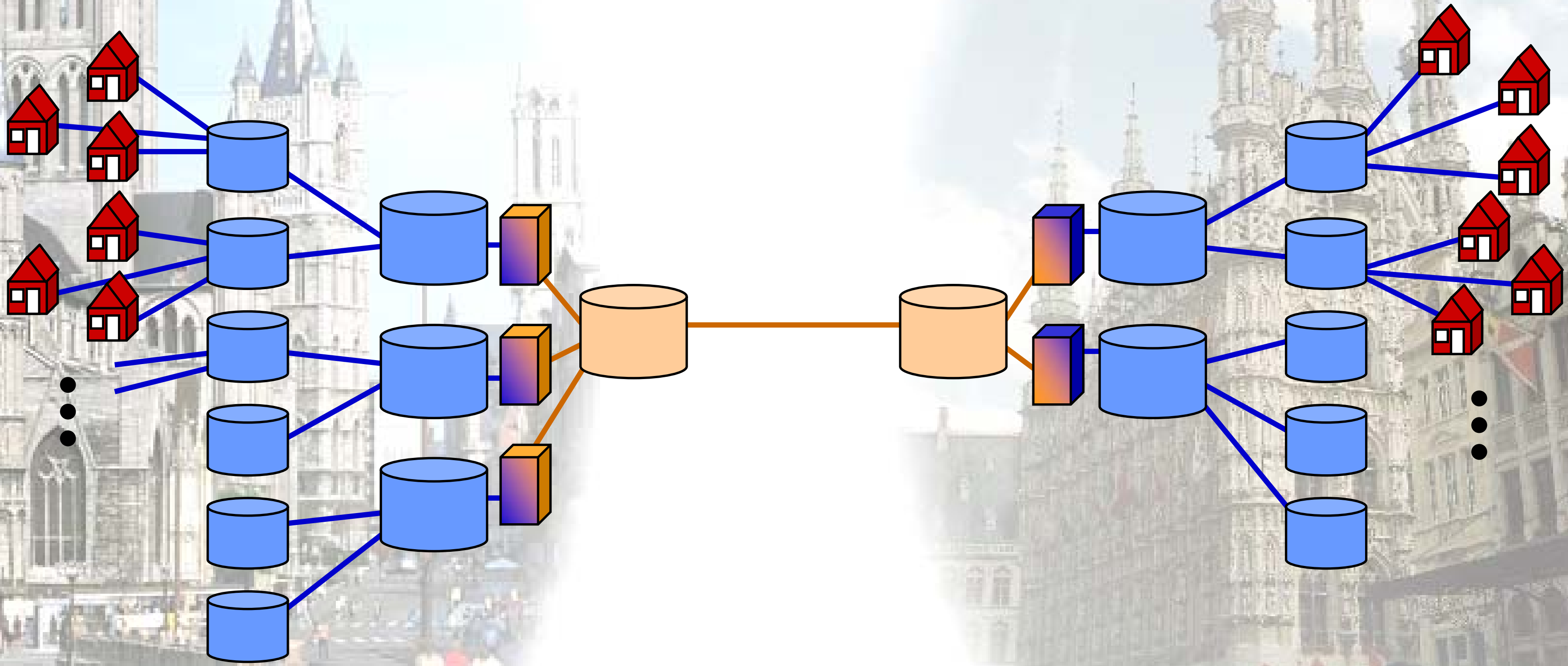
Cabinet on the curbside

submarine cable

Telecommunication networks

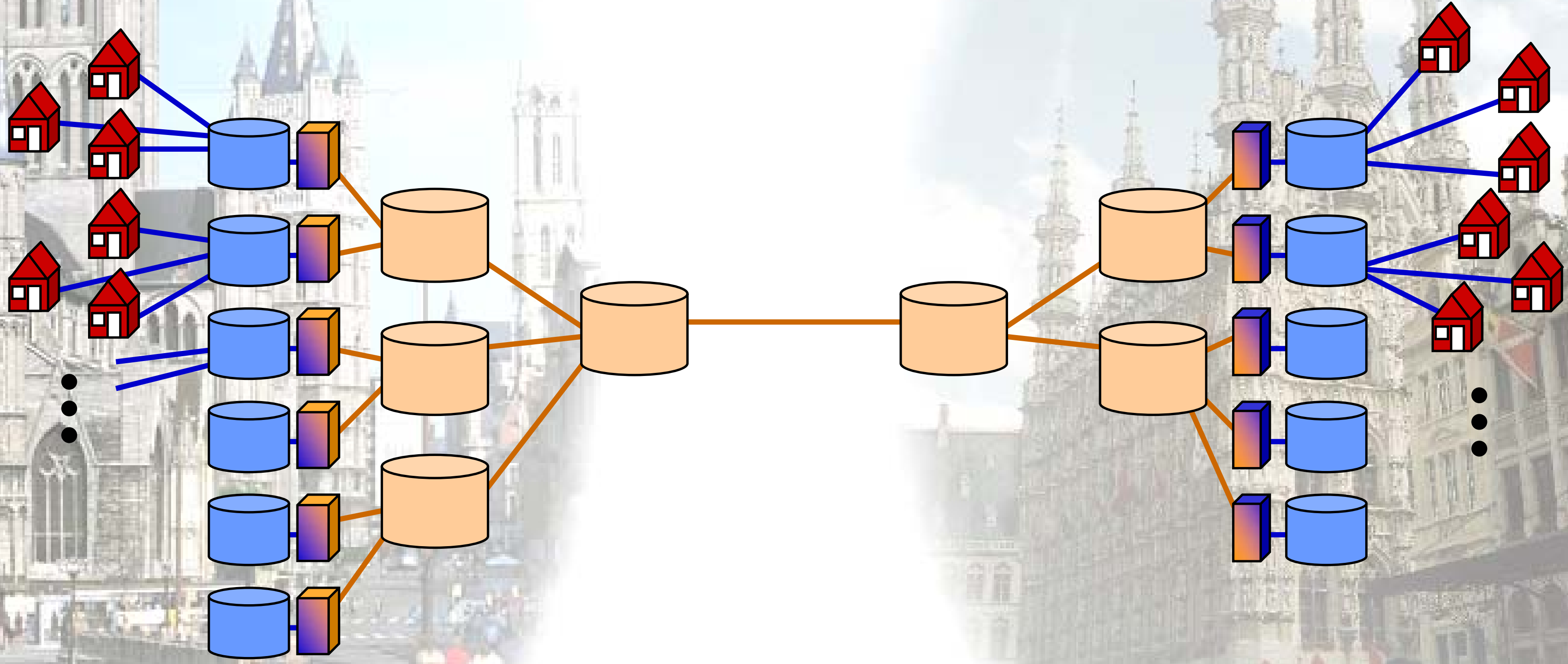


Telecommunication networks



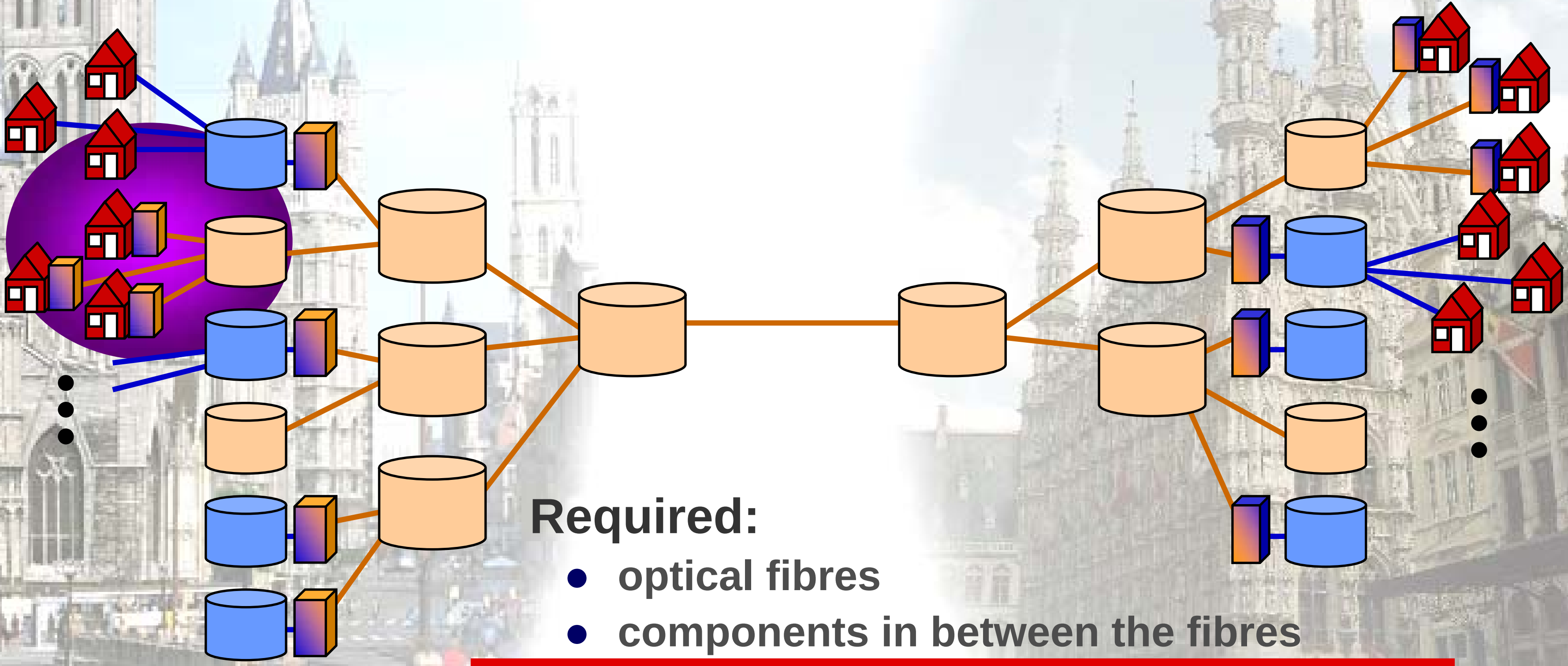
Telecommunication networks

Fiber to the curbside



Telecommunication networks

Fibre to the home

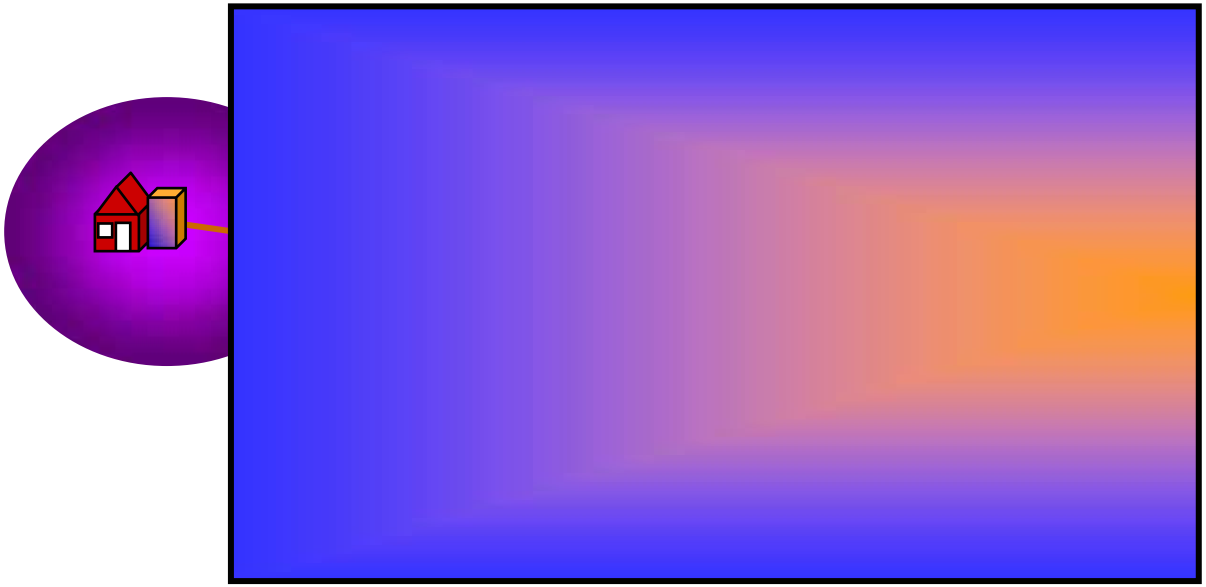


Required:

- optical fibres
- components in between the fibres
- electro-optic conversion at end points

LARGE QUANTITIES AND CHEAP

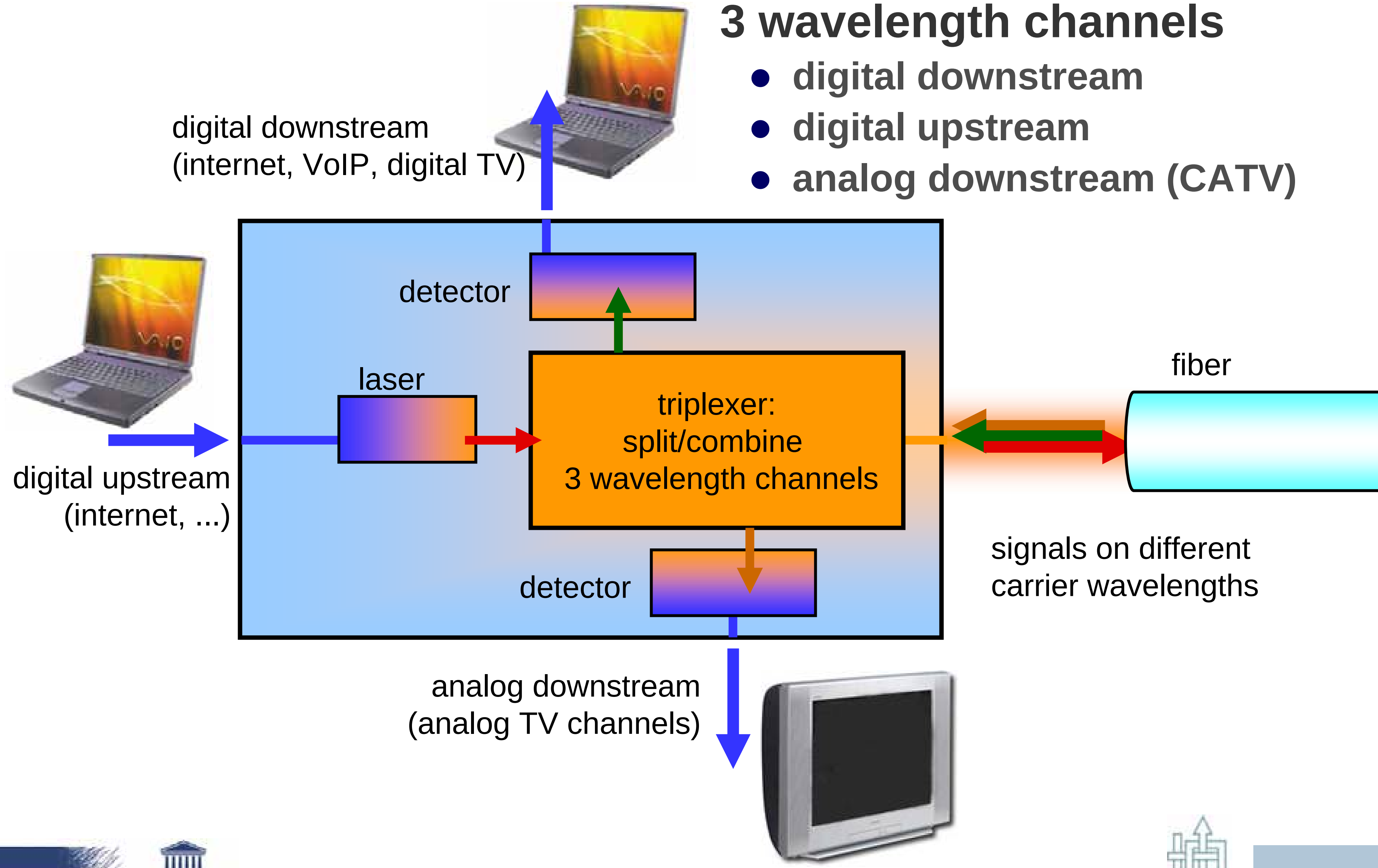
Telecommunication networks



Example: FTTH Triplexer

3 wavelength channels

- digital downstream
- digital upstream
- analog downstream (CATV)



digital downstream
(internet, VoIP, digital TV)

detector

laser

triplexer:
split/combine
3 wavelength channels

fiber

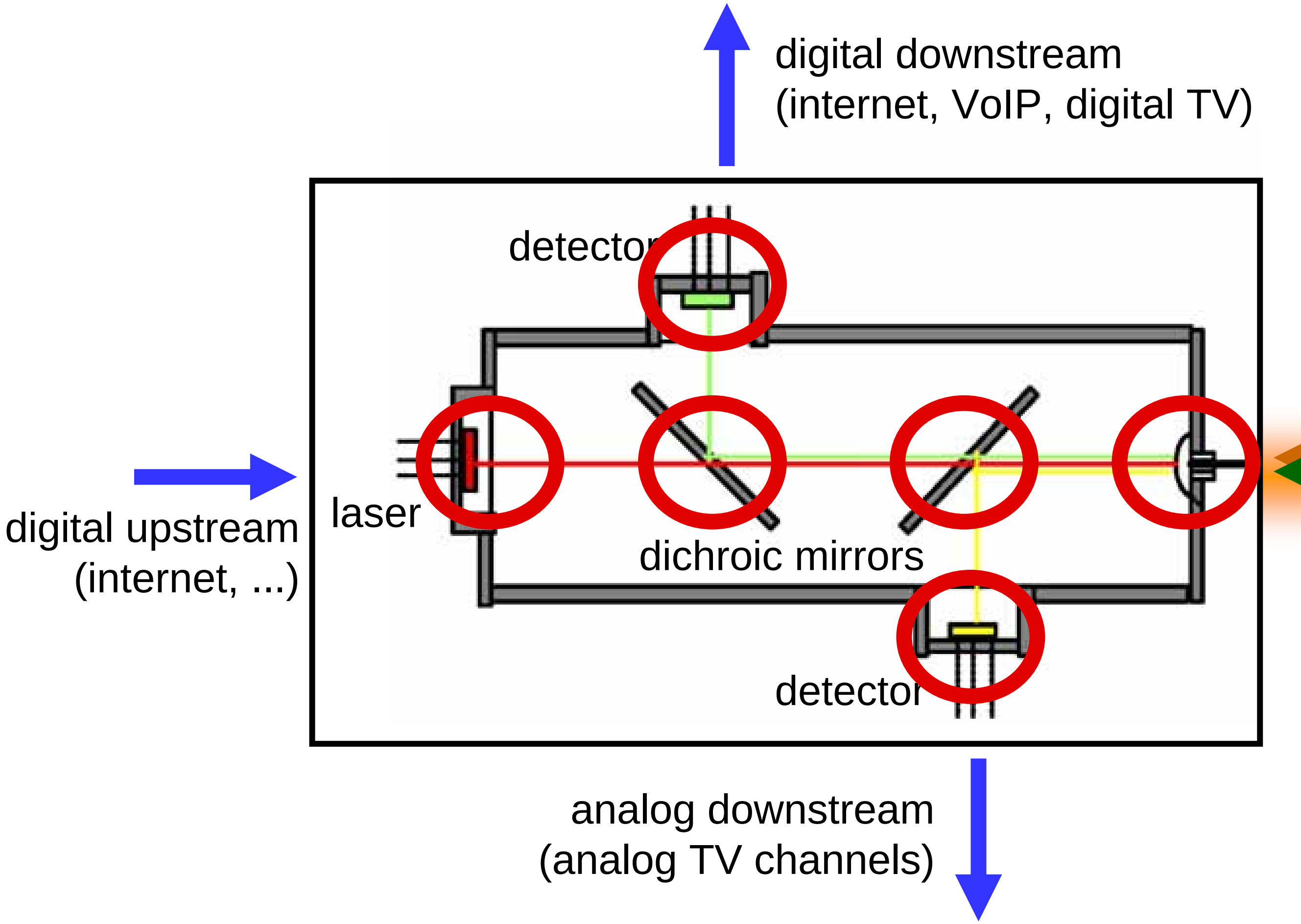
digital upstream
(internet, ...)

detector

signals on different
carrier wavelengths

analog downstream
(analog TV channels)

Example: FTTH Triplexer



digital downstream
(internet, VoIP, digital TV)

detector

fiber

digital upstream
(internet, ...)

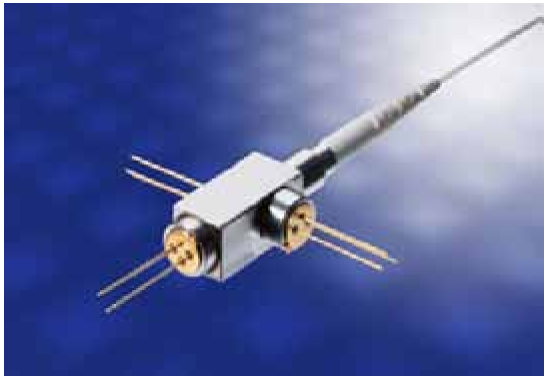
laser

dichroic mirrors

detector

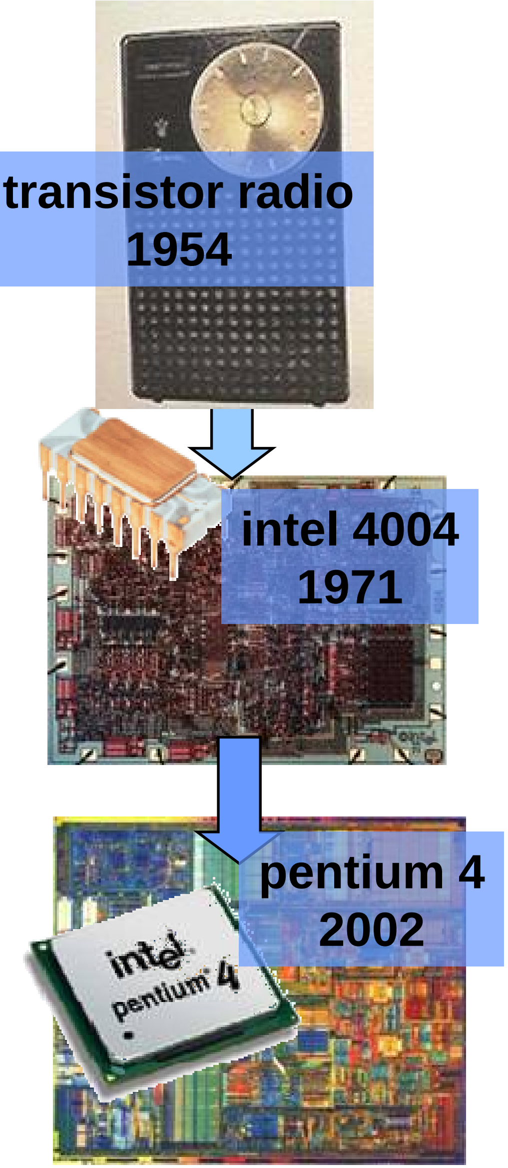
analog downstream
(analog TV channels)

Align 6 optical elements!!!



box = 20x10x10 mm

Integration of circuits

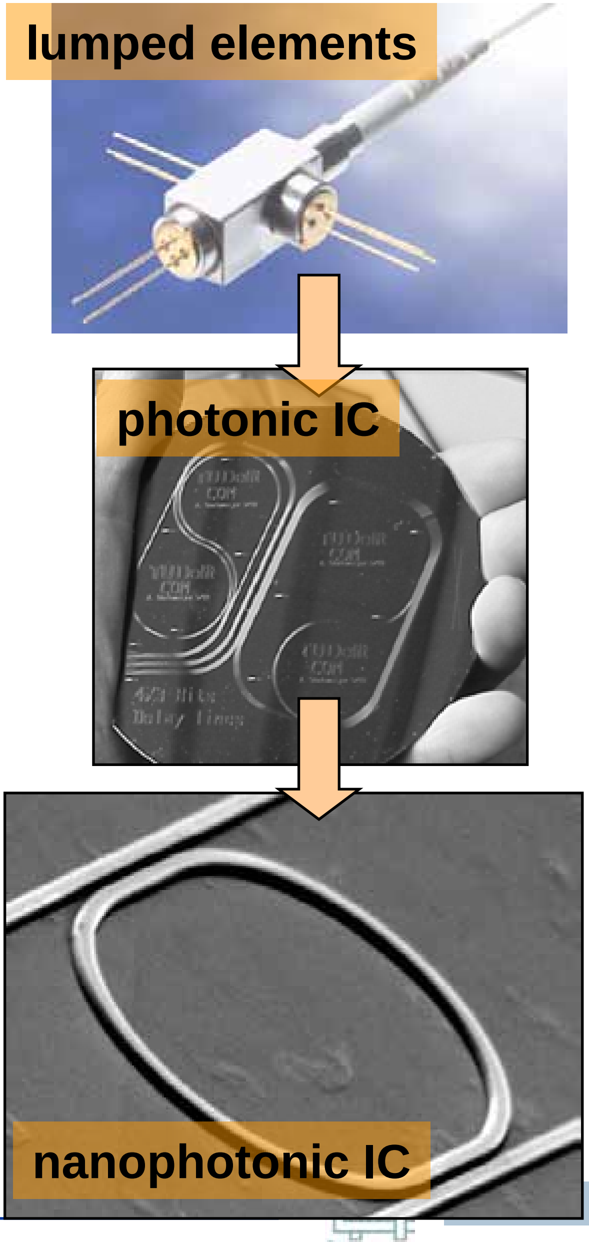

transistor radio
1954

intel 4004
1971

pentium 4
2002

= bringing various functions together on a ‘chip’

- Electronics:
  - transistors
  - metal wires for electrical connections between components
- Photonics:
  - **waveguides** to transport light between components
  - wavelength filters
  - sources and detectors


lumped elements

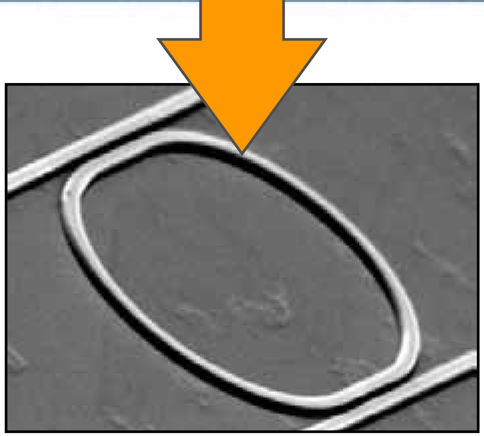
photonic IC

nanophotonic IC

Integrated Optical Sensors

Strain sensor

- measure reflection of fiber grating
- requires “long” fiber
- complex mounting



Ring resonator

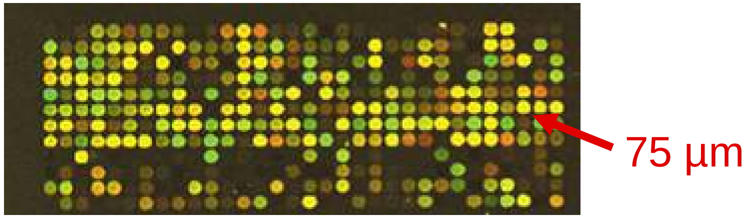
- resonance peak depends on circumference
- peak shifts when strained

Integrated Biosensors

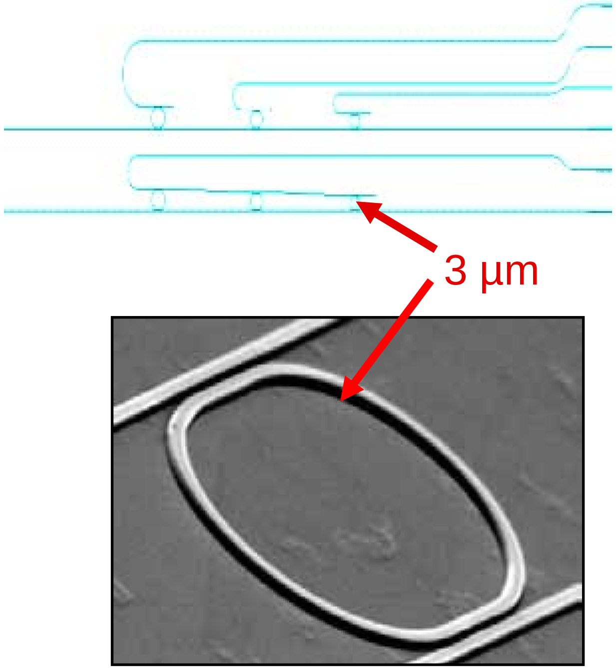
Today’s Commercial biosensors:

Integrated photonic biosensor:

Elisa test for protein binding



DNA microarray



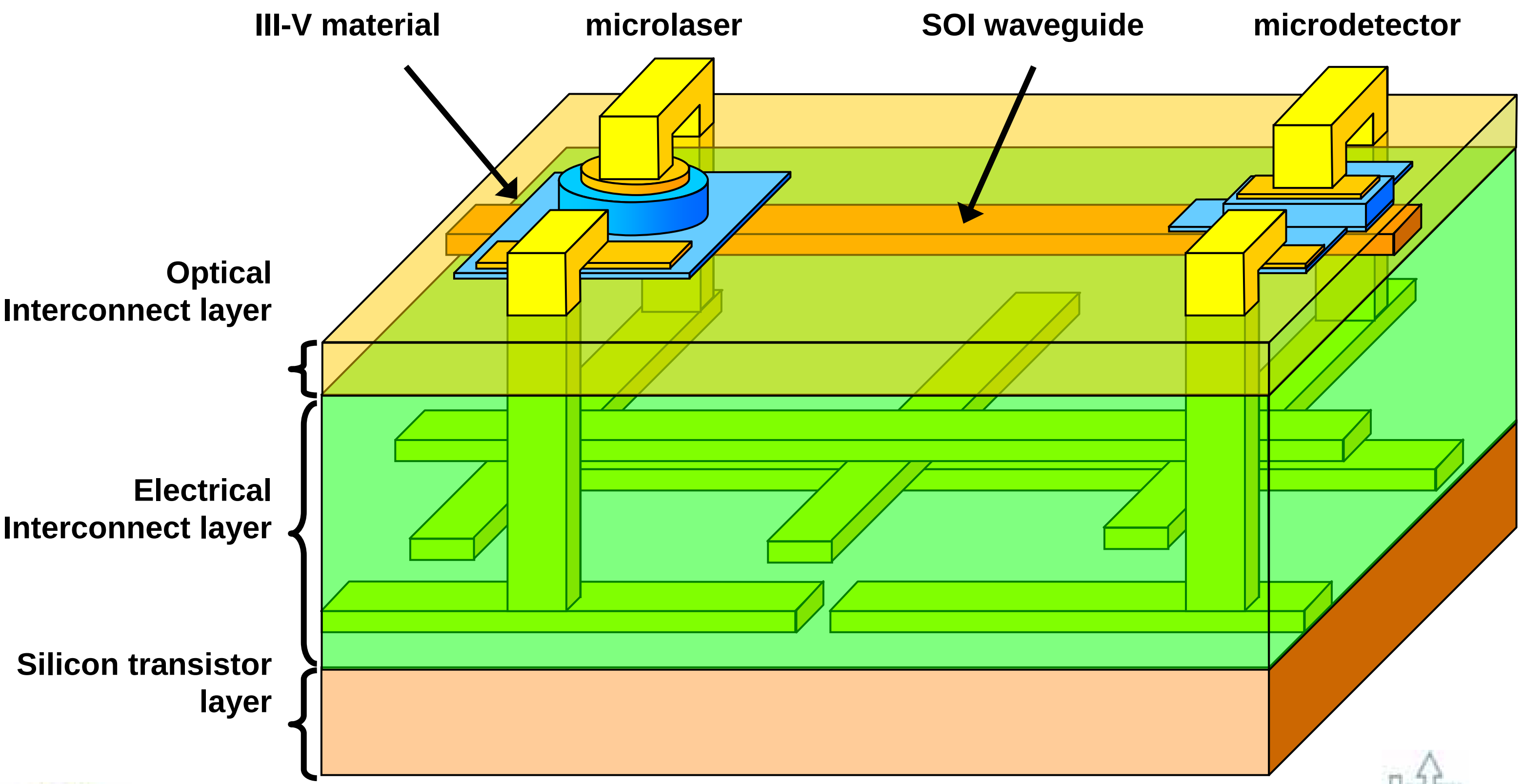
- → Complex and slow label-processes
- → Complex interpretation of results
- → Big amounts of analyte

- → No labeling
- → Quantitative and fast results
- → Very small amounts of analyte

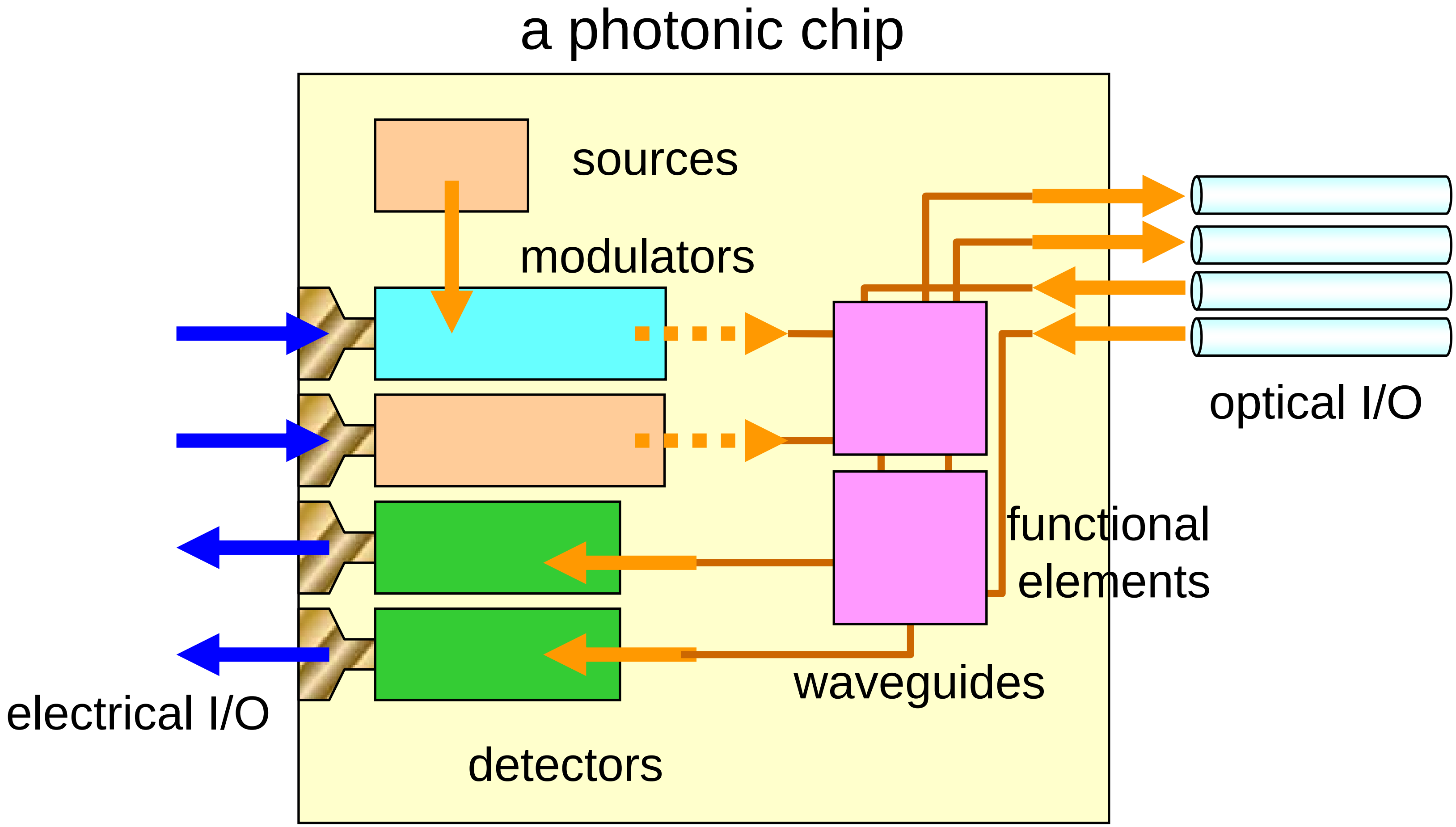
On-chip interconnects

Replace long-range metallic interconnects

- large bandwidth
- no ohmic losses and heating in waveguide



I make a photonic IC, and I need...



Overview of this presentation

Background on Photonics

- What’s the use?
- How does a waveguide work?
- Photonic Crystals
- SOI Nanophotonics

What is light?
How can we guide light?
What is a good waveguide?

Worldwide State-of-the-art

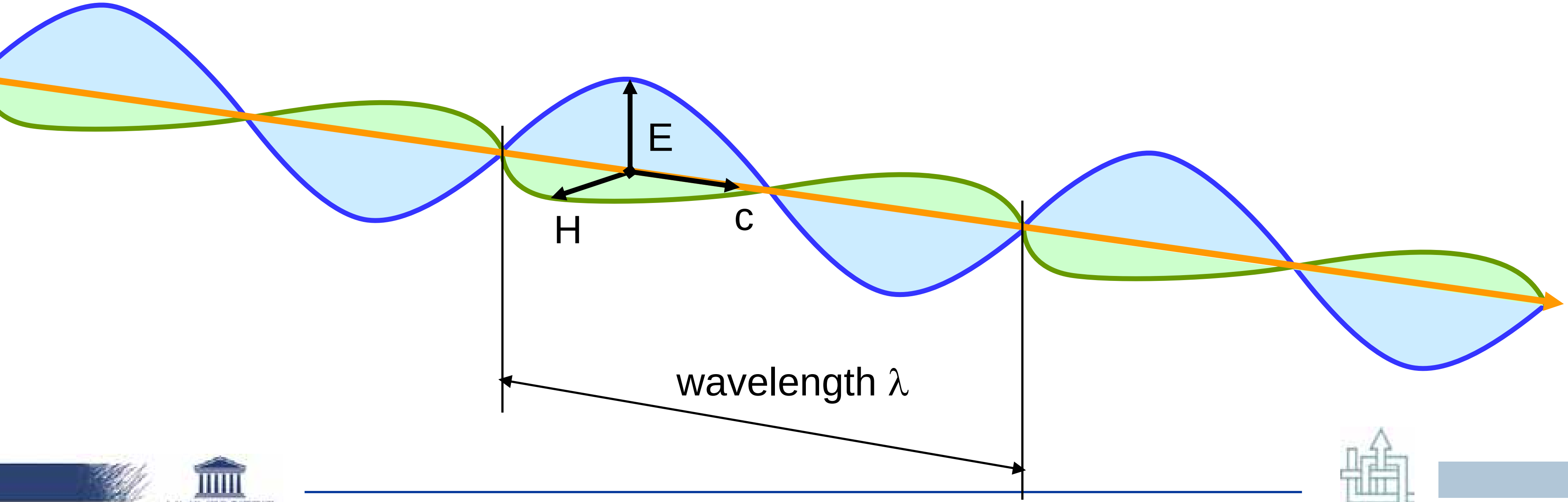
Conclusion

Light = Electromagnetic Wave

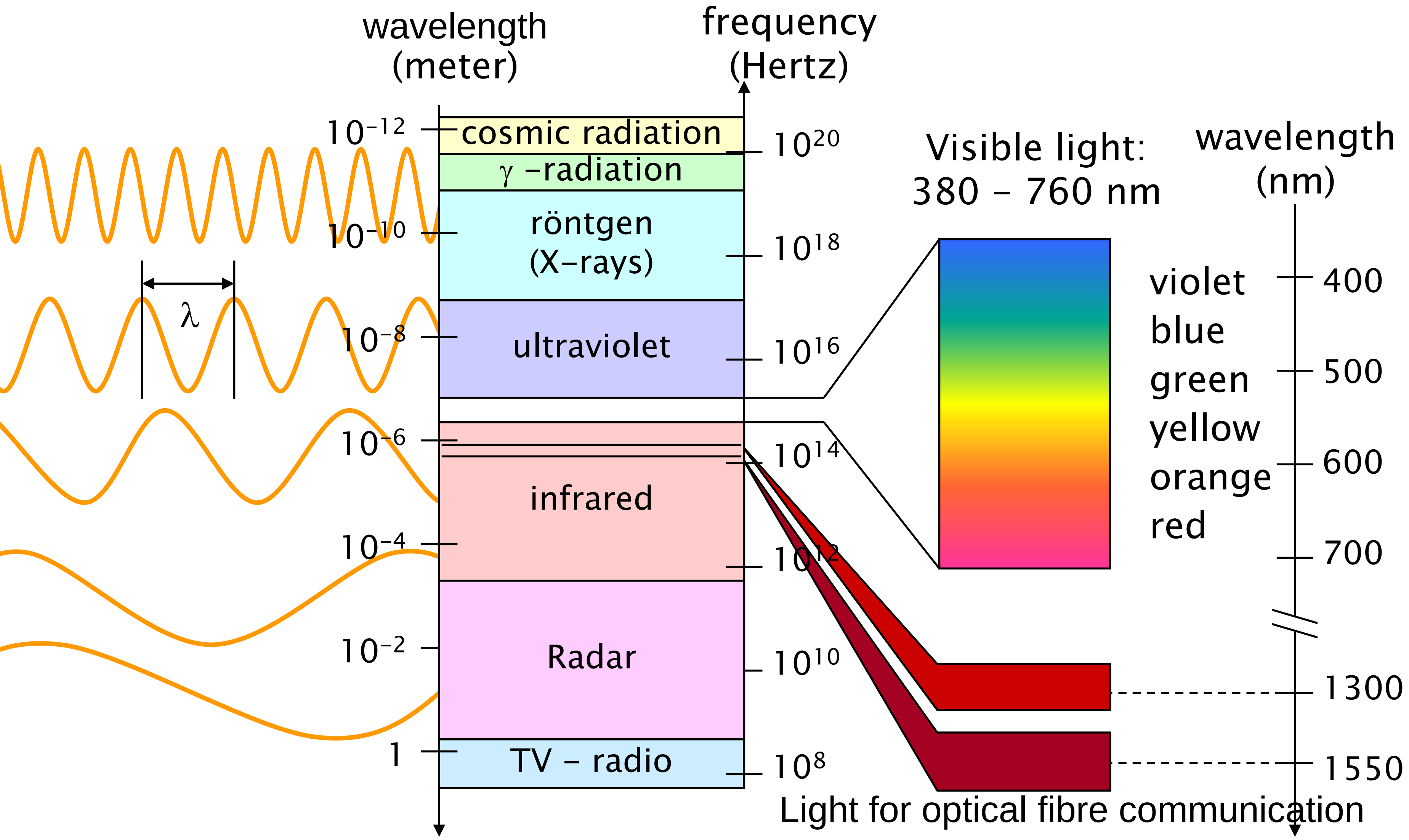
Ray of light ≈ Electromagnetic wave

- Propagates at speed of light **c**
- Electrical oscillation **E**
- Magnetic oscillation **H**
- Oscillation frequency **f**
- with a wavelength λ

$$f \times \lambda = c$$



Electromagnetic Radiation



Propagation of light

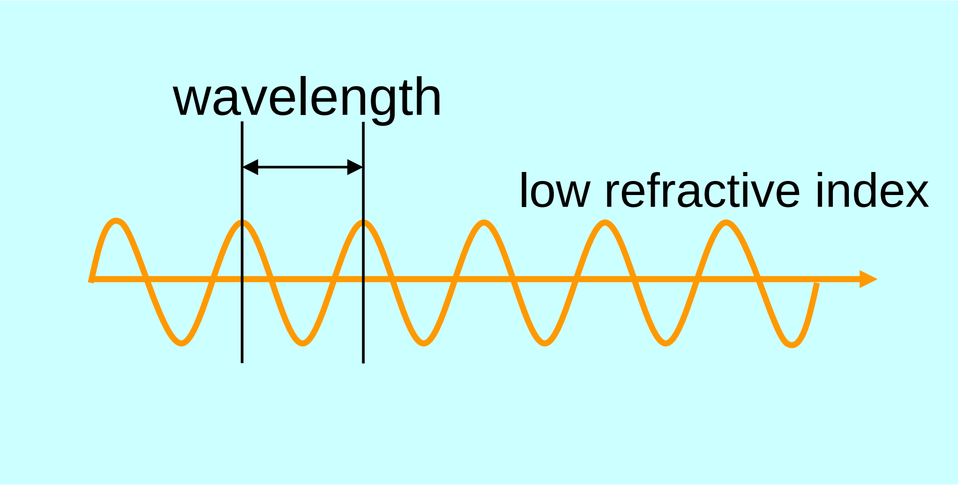
In vacuum: light propagates at the speed of light c

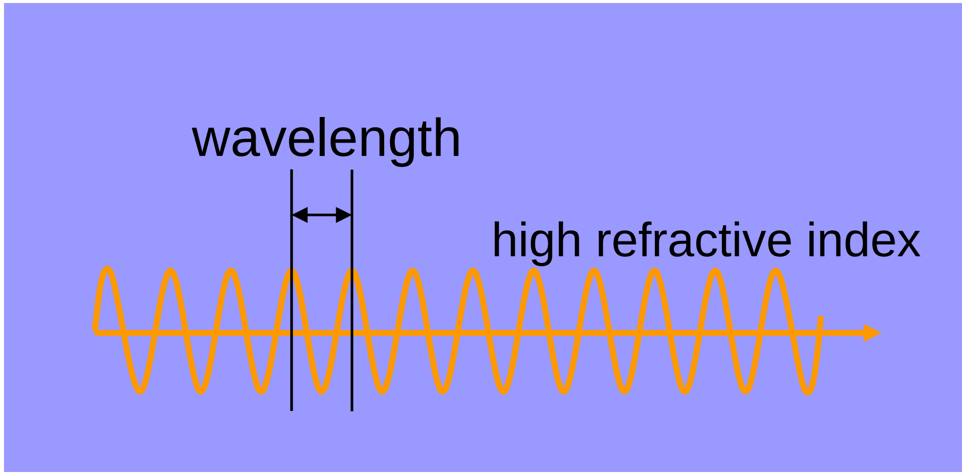
In material: light propagates n times slower

↓

n = refractive index

wavelength becomes n times shorter for the same frequency



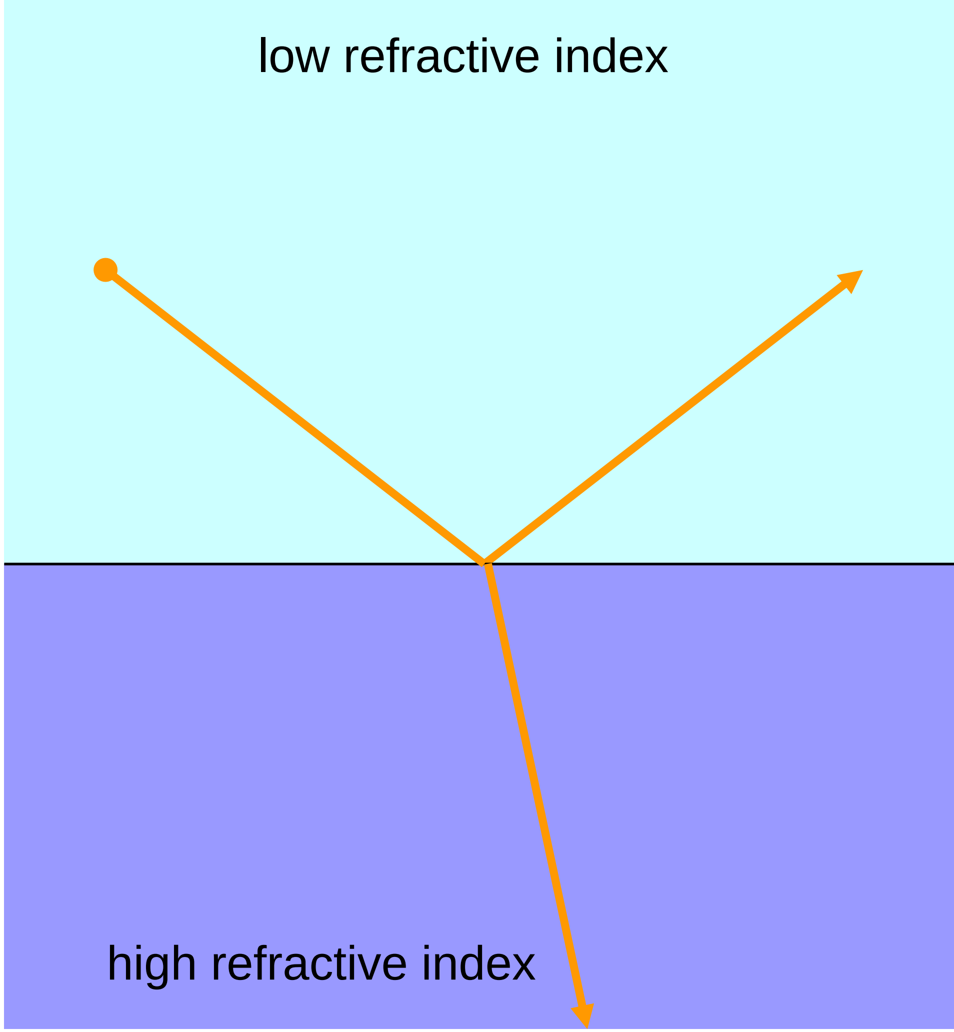


Light at an interface

Change in refractive index n

- **Light rays change direction**
- **Light is partially reflected**

Effect is more pronounced with a stronger contrast in refractive index



Total internal reflection

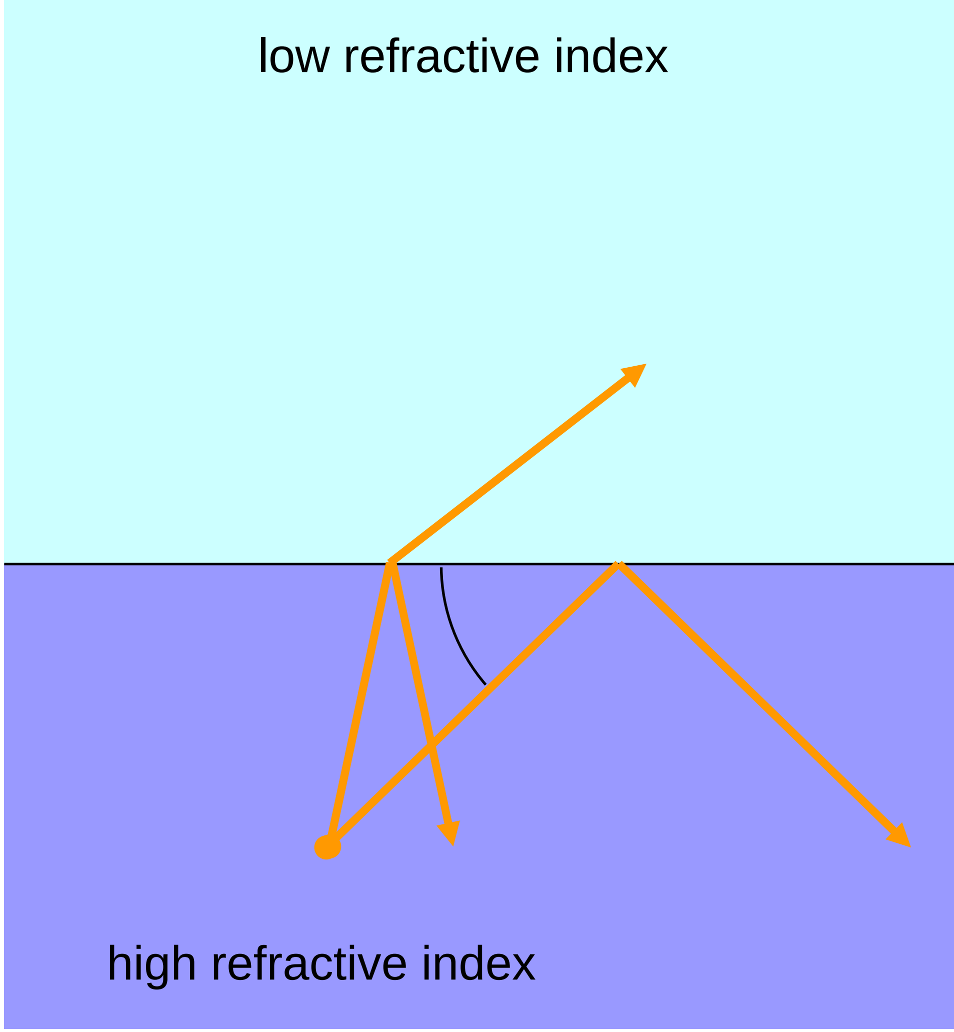
‘inside to outside’:

Very oblique rays are totally reflected

= Total internal reflection

The critical angle with the surface is larger for a stronger contrast in refractive index

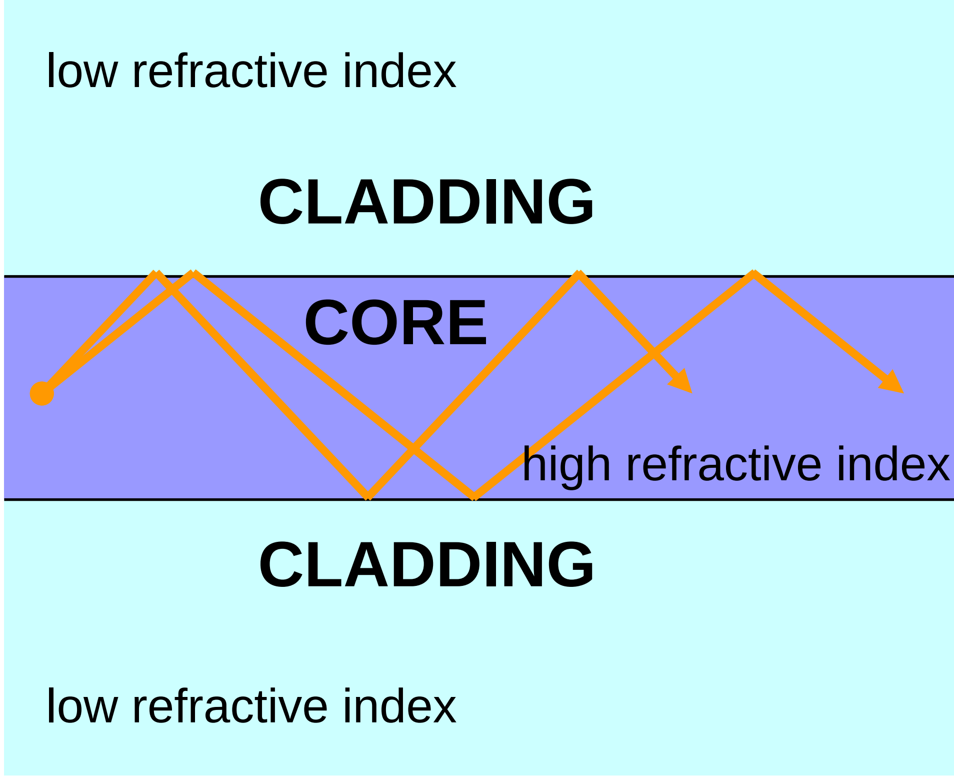
(less oblique rays are also reflected)



Layered (Slab) Waveguide

‘Sandwich’ of material with a high refractive index between material with a low refractive index

Light is guided by total internal reflection in a core of high refractive index surrounded by a cladding of low refractive index


low refractive index

CLADDING

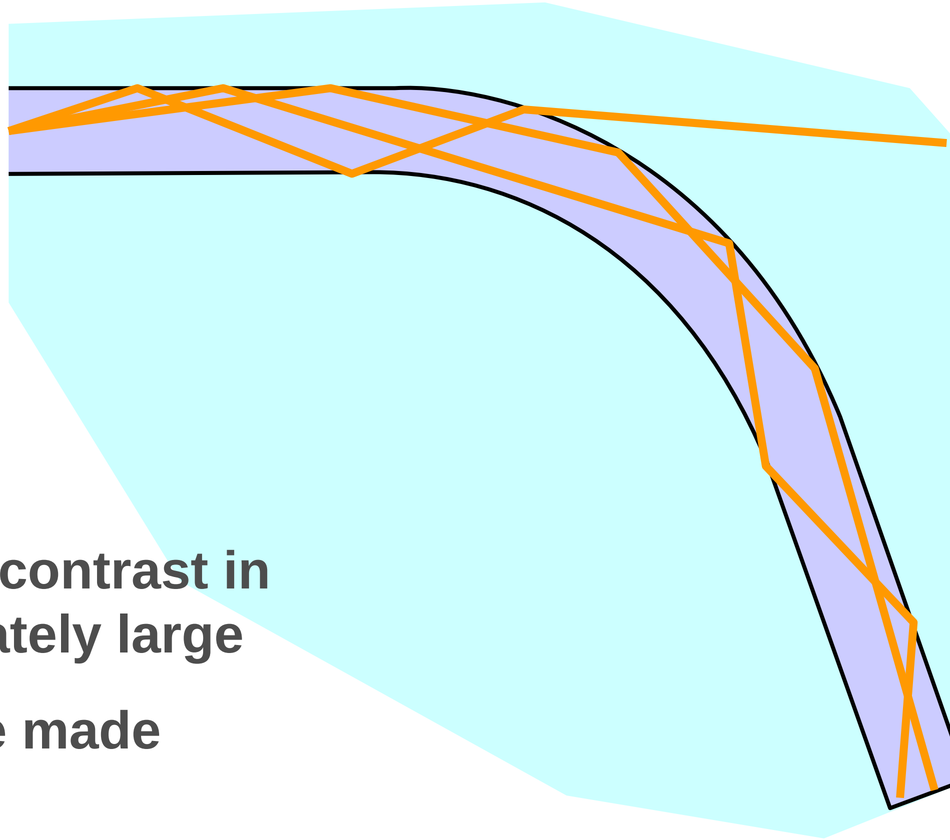
CORE

high refractive index

CLADDING

low refractive index

Bends in waveguides



Some rays can escape from the waveguide

- Better confinement if the contrast in refractive index is adequately large
- Less loss if the bends are made sufficiently wide

Sharp bends possible with large refractive index contrast

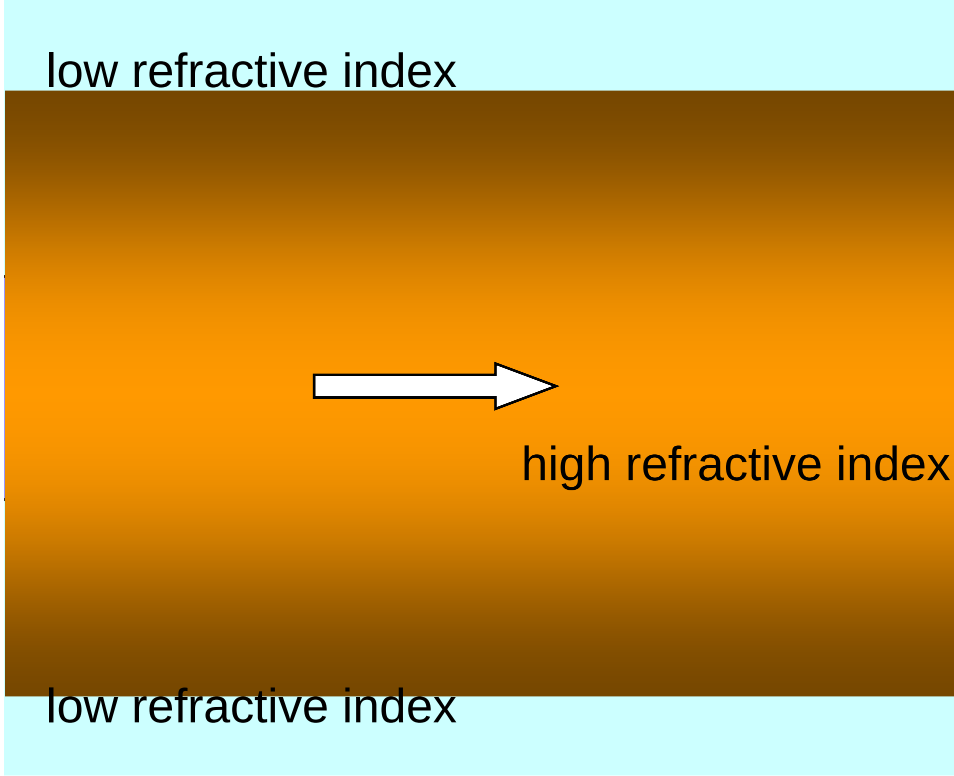
Mode of a waveguide

Thin core: Rays are an inaccurate model

Light is located in a smeared-out 'blob' in and around the waveguide core

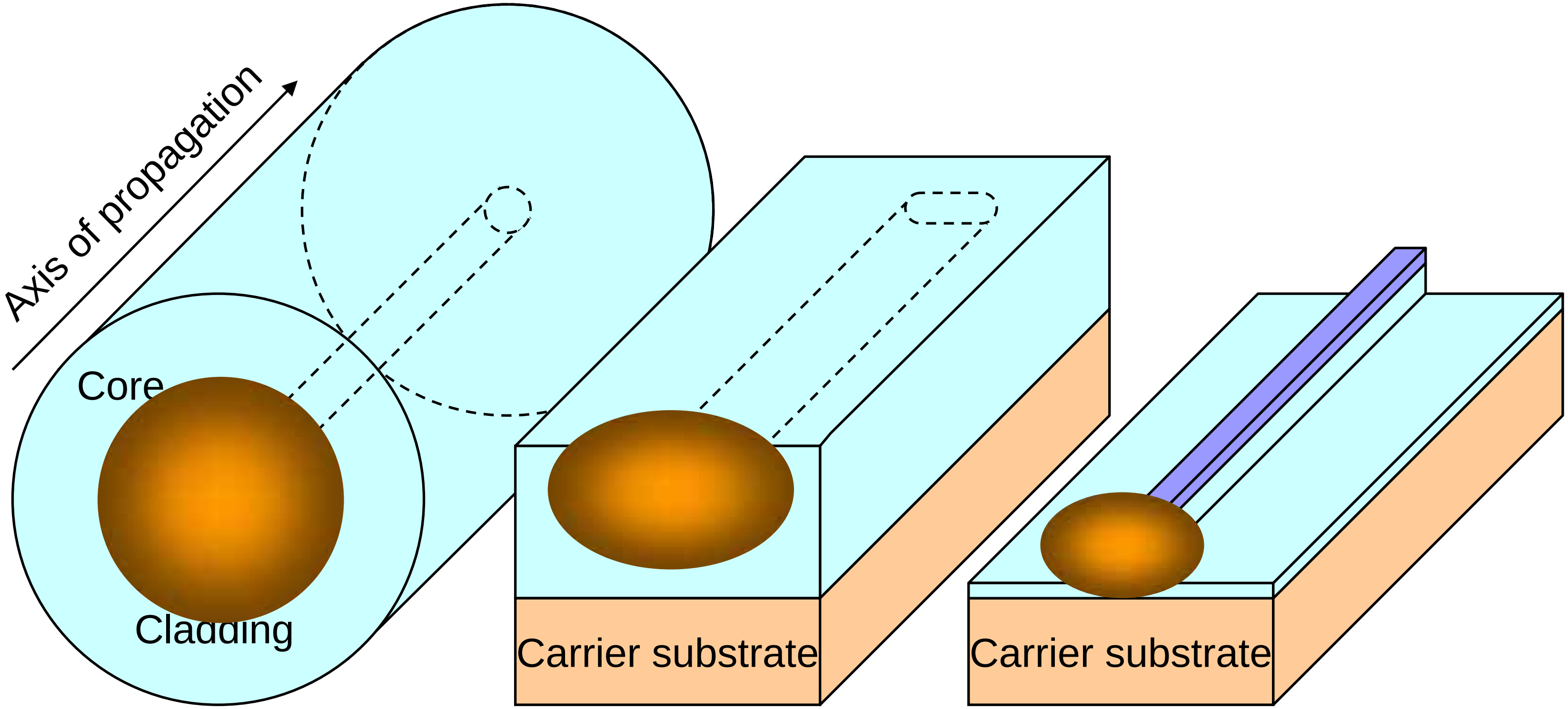
= a mode

- **a mode propagates as a single entity**
- **Guided modes: remain localised around the core**



Waveguides

Refractive index contrast in more directions: confine light in a core



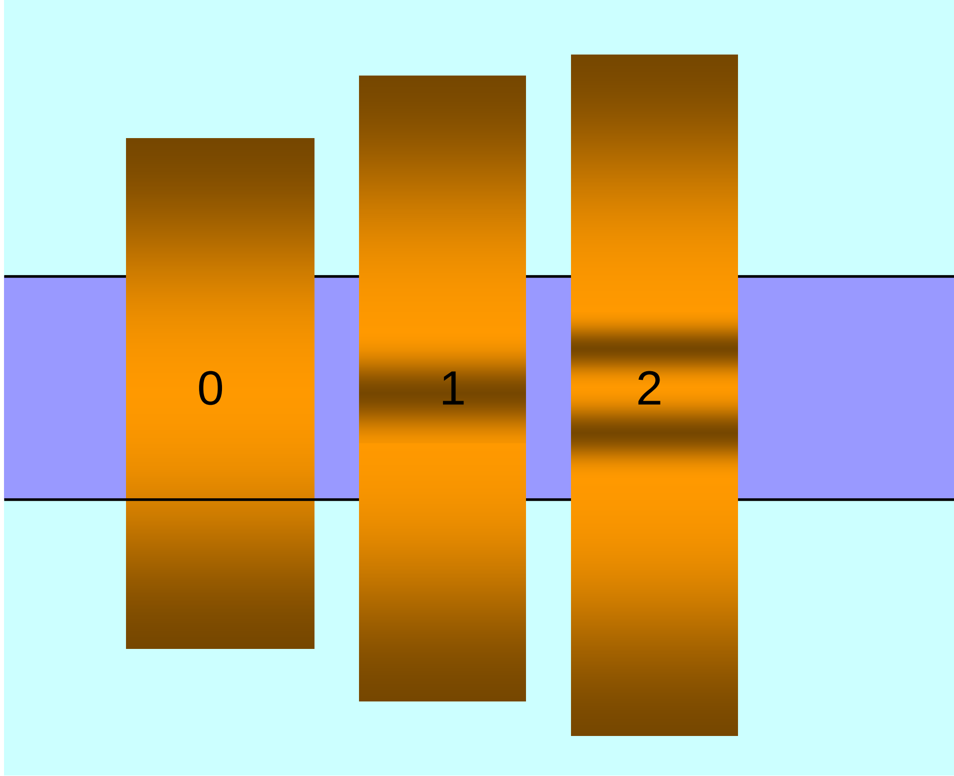
Guided modes in a waveguide

Some waveguides can support multiple guided modes

Mode 0 (ground mode) is the most useful

- best confinement:
  Smallest cross section
- most elegant distribution
  (no zeroes)

We'd like a waveguide that only supports a ground mode
(= single-mode waveguide)



Single-mode waveguide

For telecommunication: Waveguides should guide only a single mode:
Core must be sufficiently small

- **Optical fibres (low refractive index contrast):**
  Core diameter ~ 10µm

Larger refractive index contrast
smaller core

- **Waveguides in semiconductor and air**
  (high index contrast): Core ~ 0.2 x 0.5µm.

Reducing waveguides in size

Today's circuits: Large bend radius

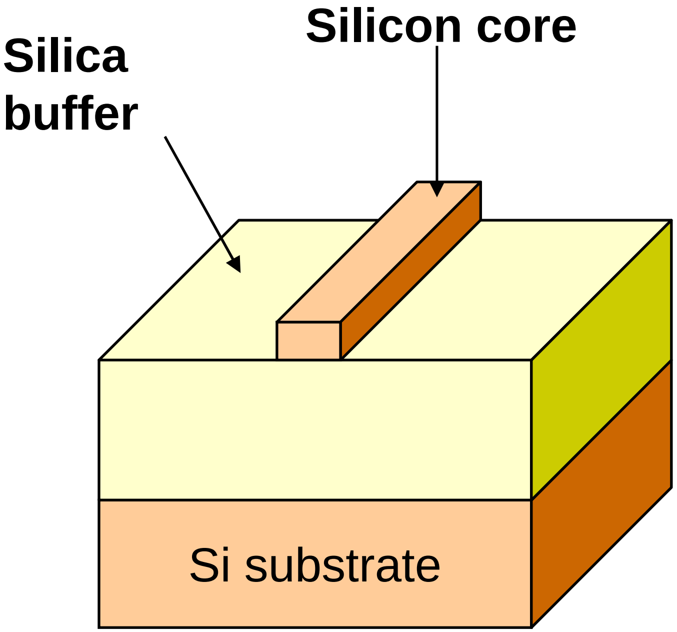
Reduce bend radius:

increase refractive index contrast
From 1.46-to-1.44 to 3.45-to-1

SEMICONDUCTORS AND AIR

Keep only one guided mode:
Reduce dimensions
From 10µm to 0.5µm

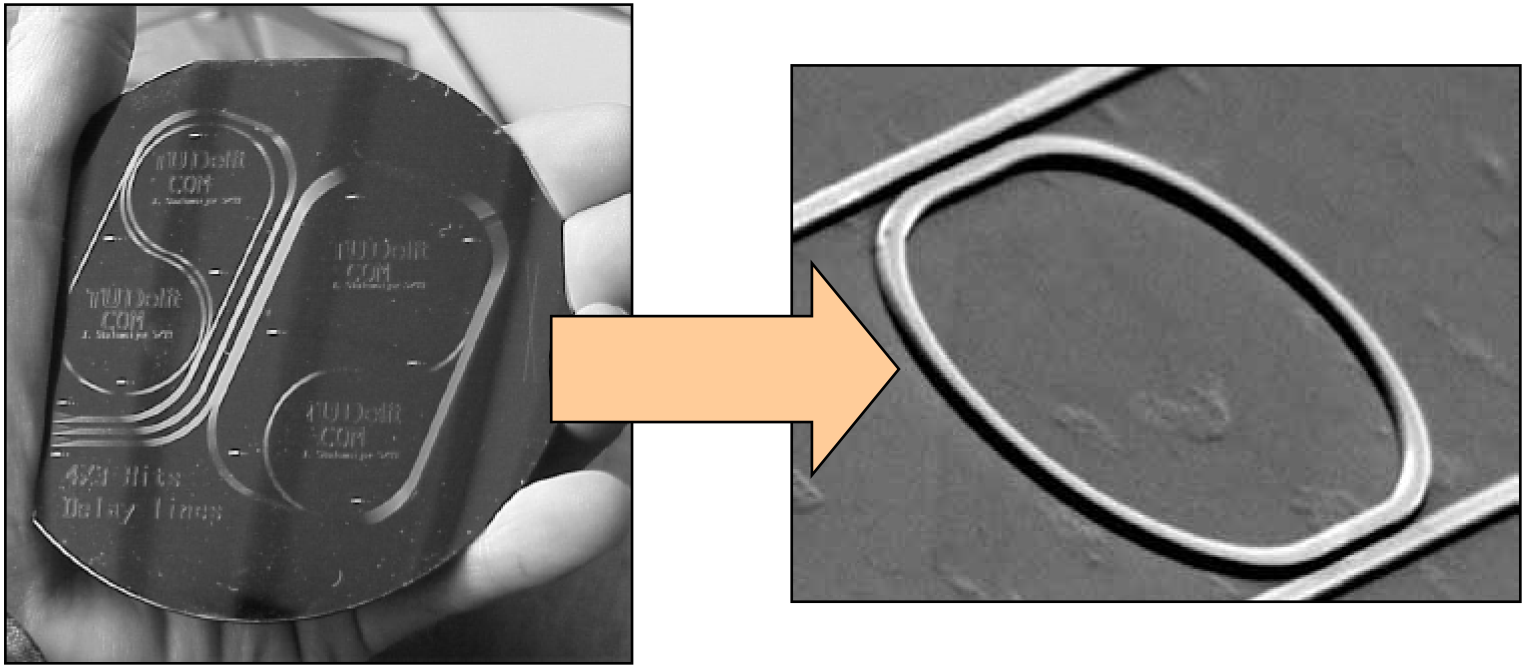
'PHOTONIC WIRES'



Waveguide circuits

1999

2003: ‘Photonic wire’



Silica-on-Silicon

Contrast: 1.46 to 1.44

Bend radius = 2cm

Silicon-on-Insulator

Contrast: 3.45 to 1

Bend radius = 3-5µm

Overview of this presentation

Background on Photonics

- What’s the use?
- How does a waveguide work?
- Photonic Crystals
- SOI Nanophotonics

UGent - IMEC achievements

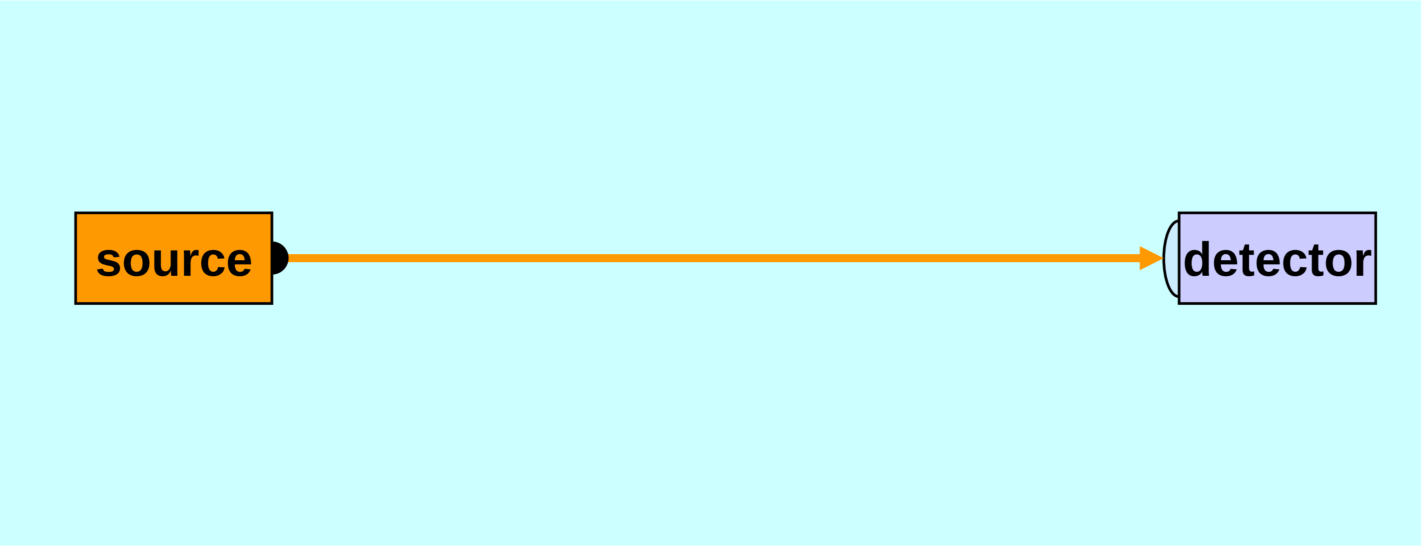
- Wha
- Som

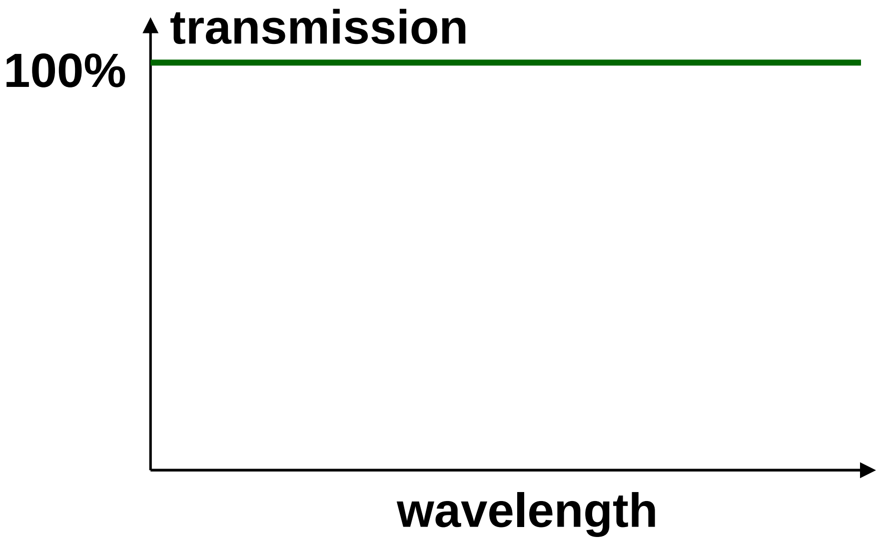
Worldwide State-of-the-art

Conclusion

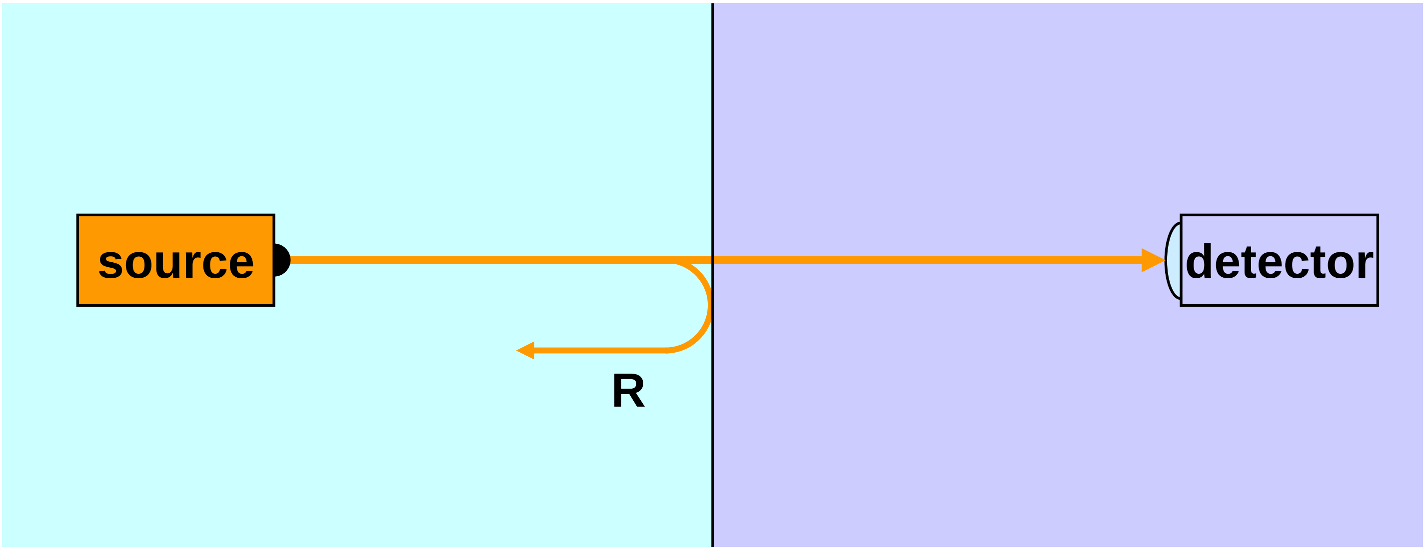
What is a photonic crystal?
What can we use it for?

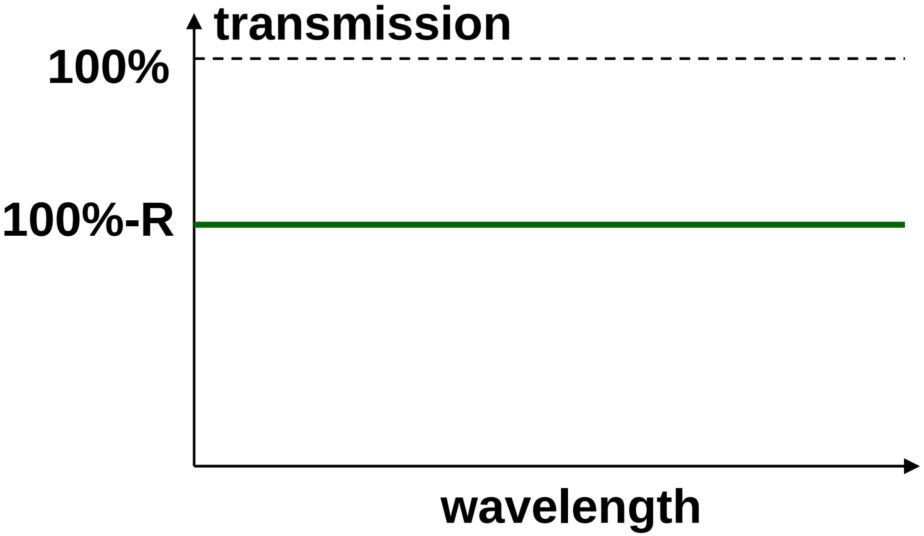
A uniform material



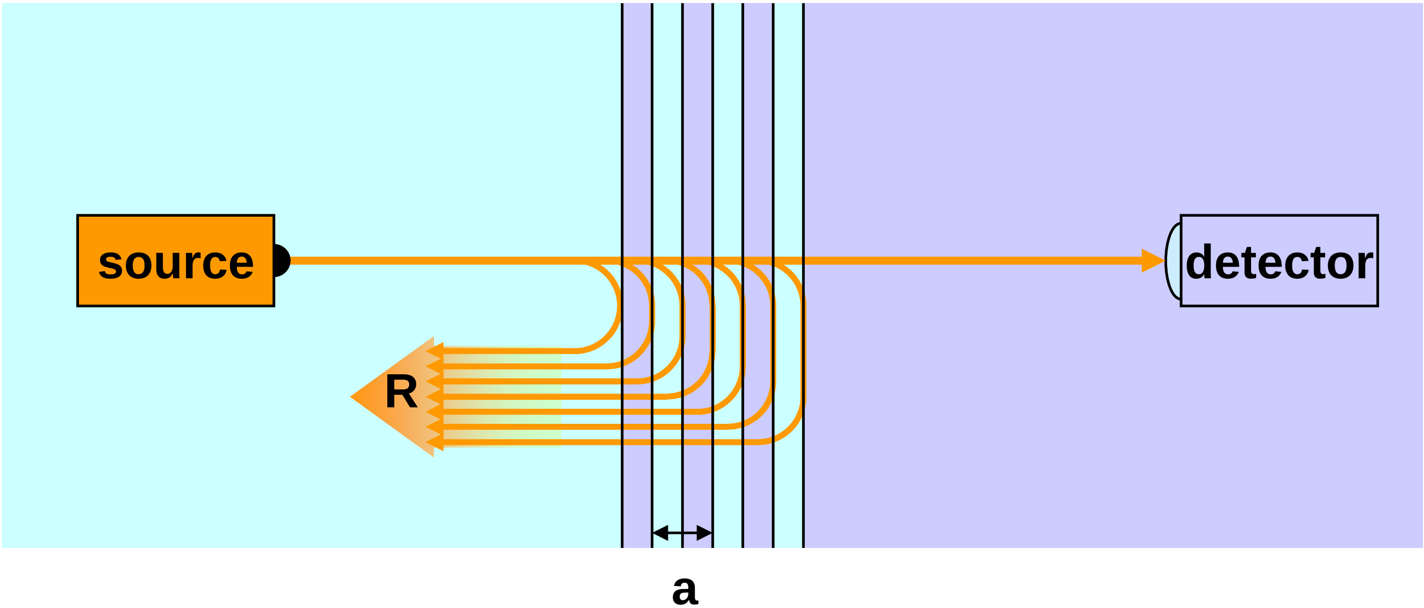


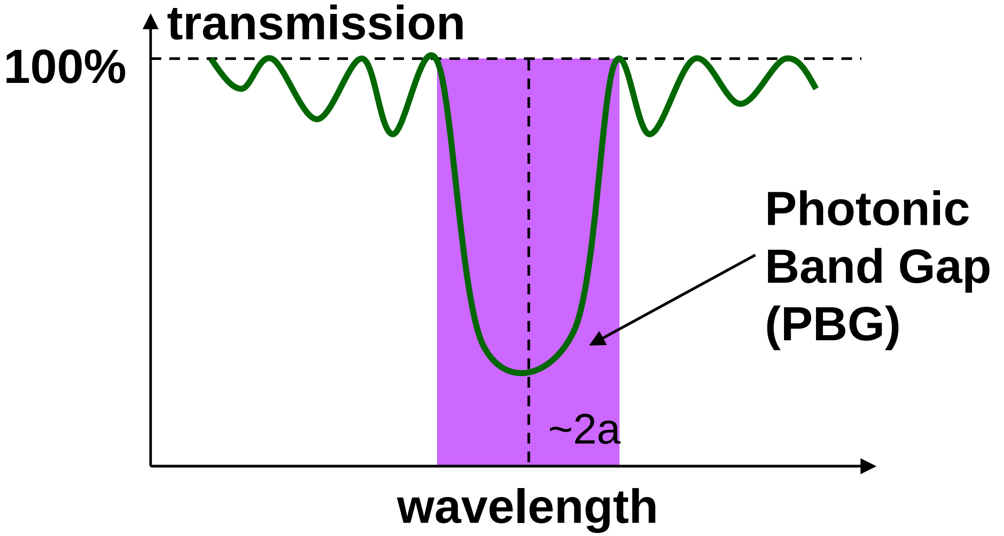
One interface



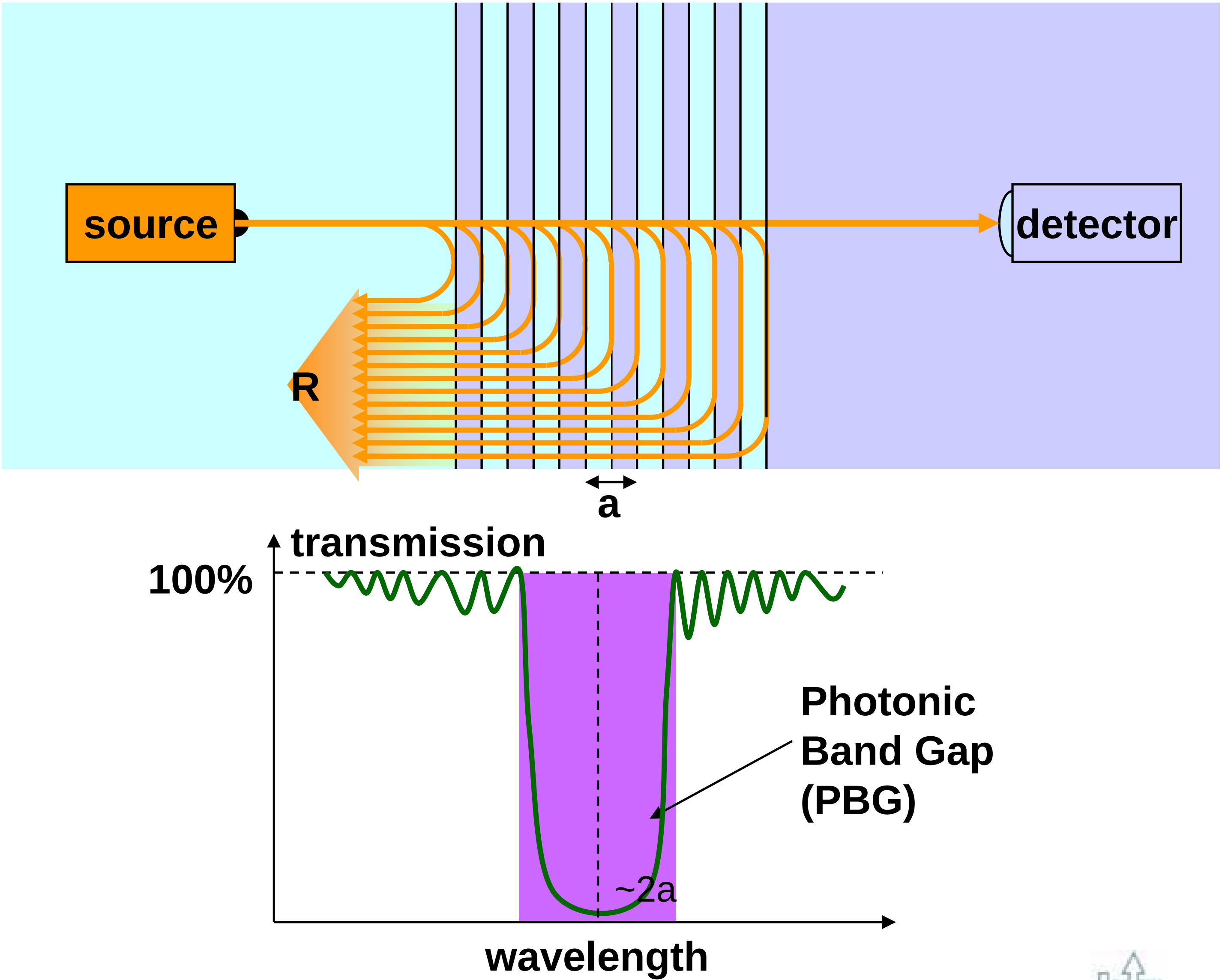


A periodically layered structure

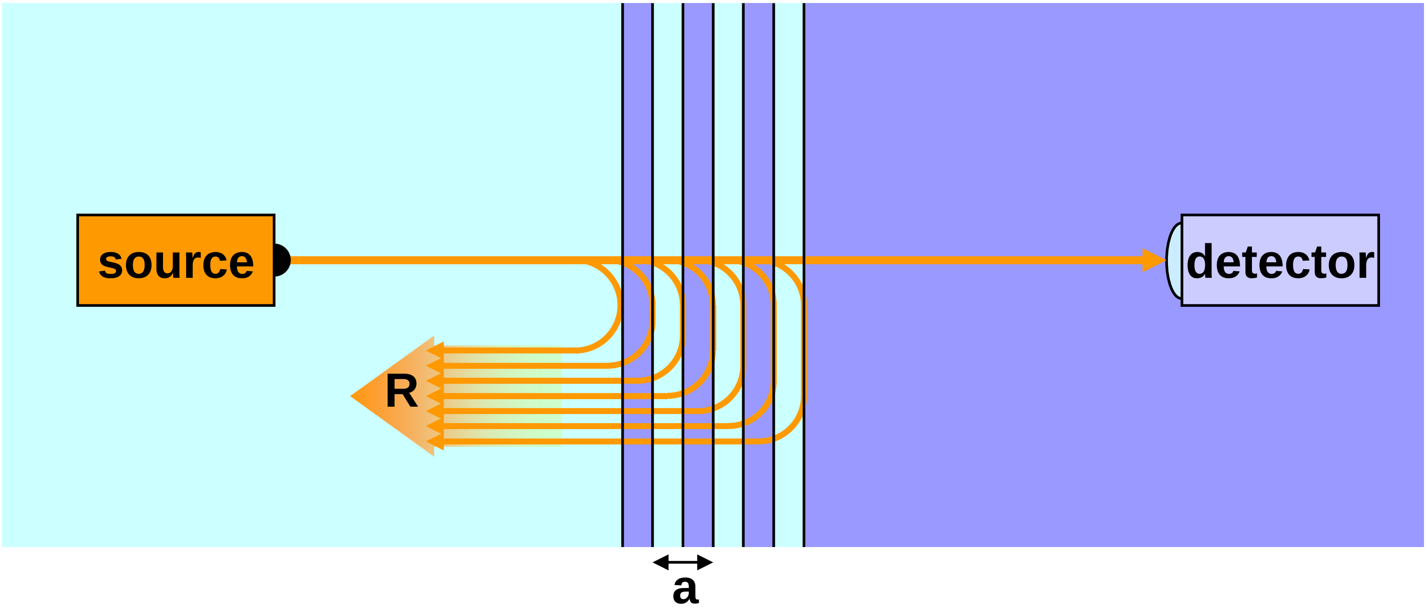


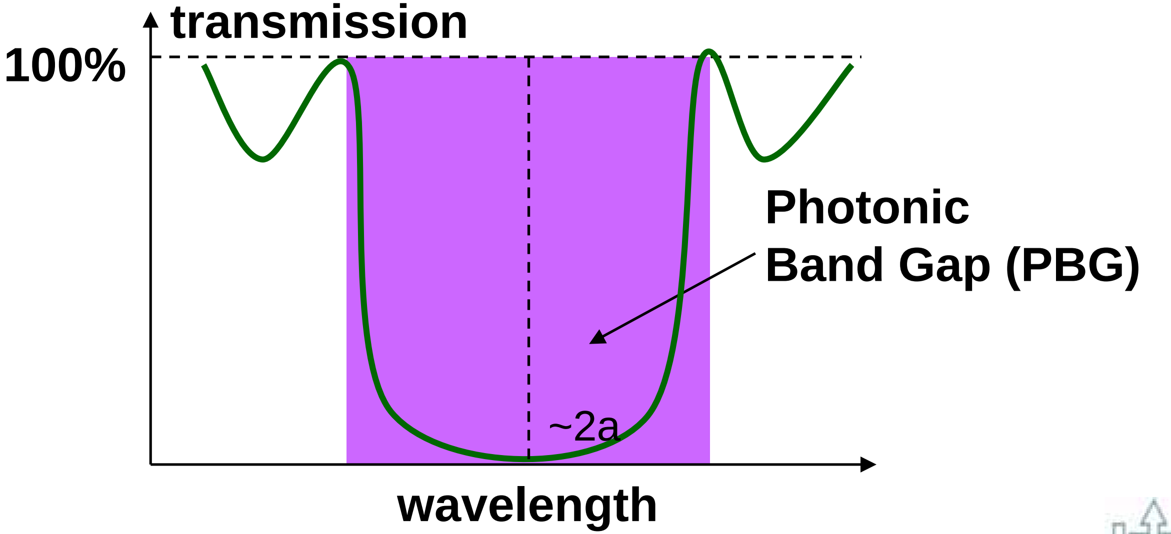


Additional layers



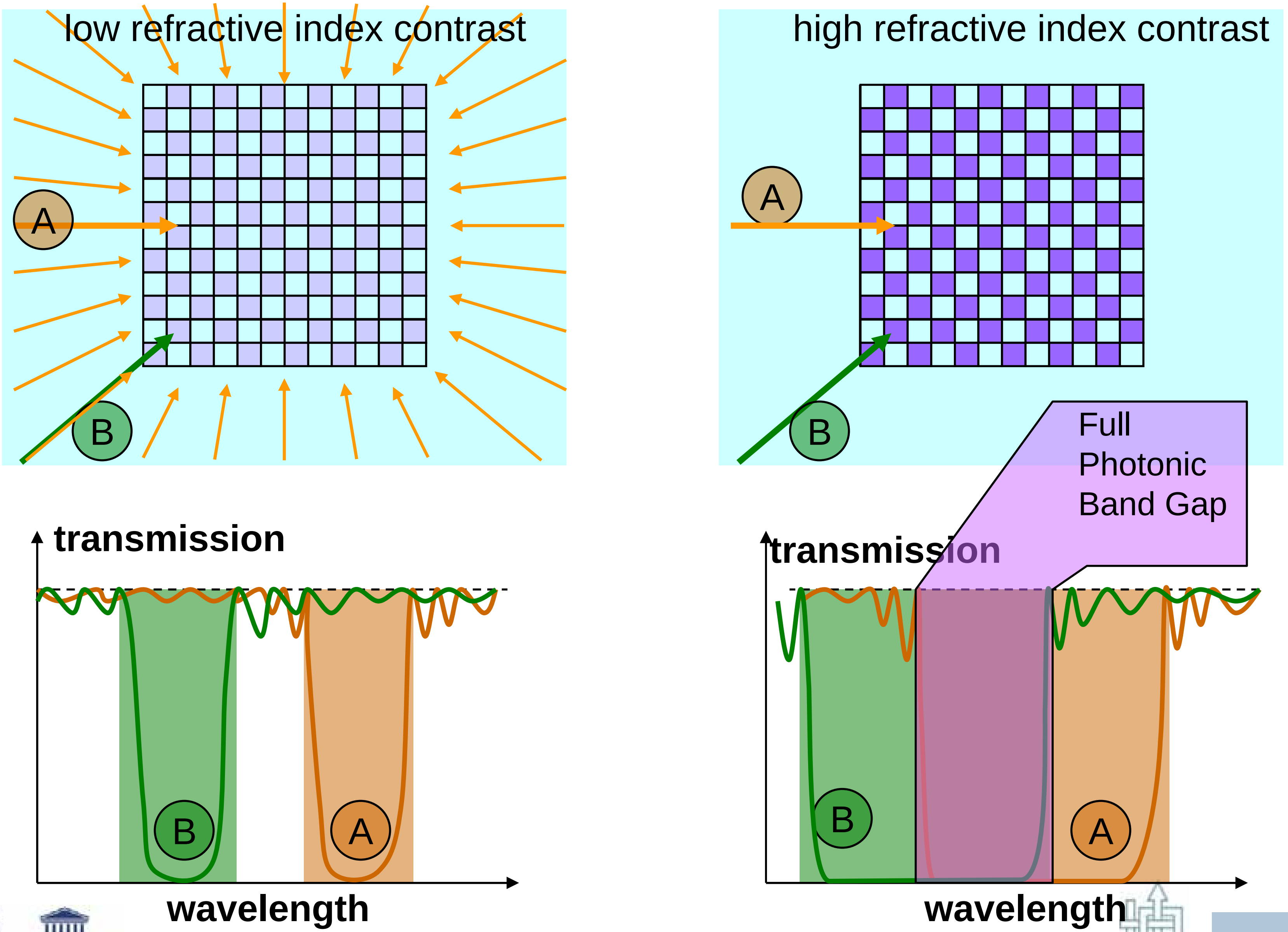
Higher index contrast





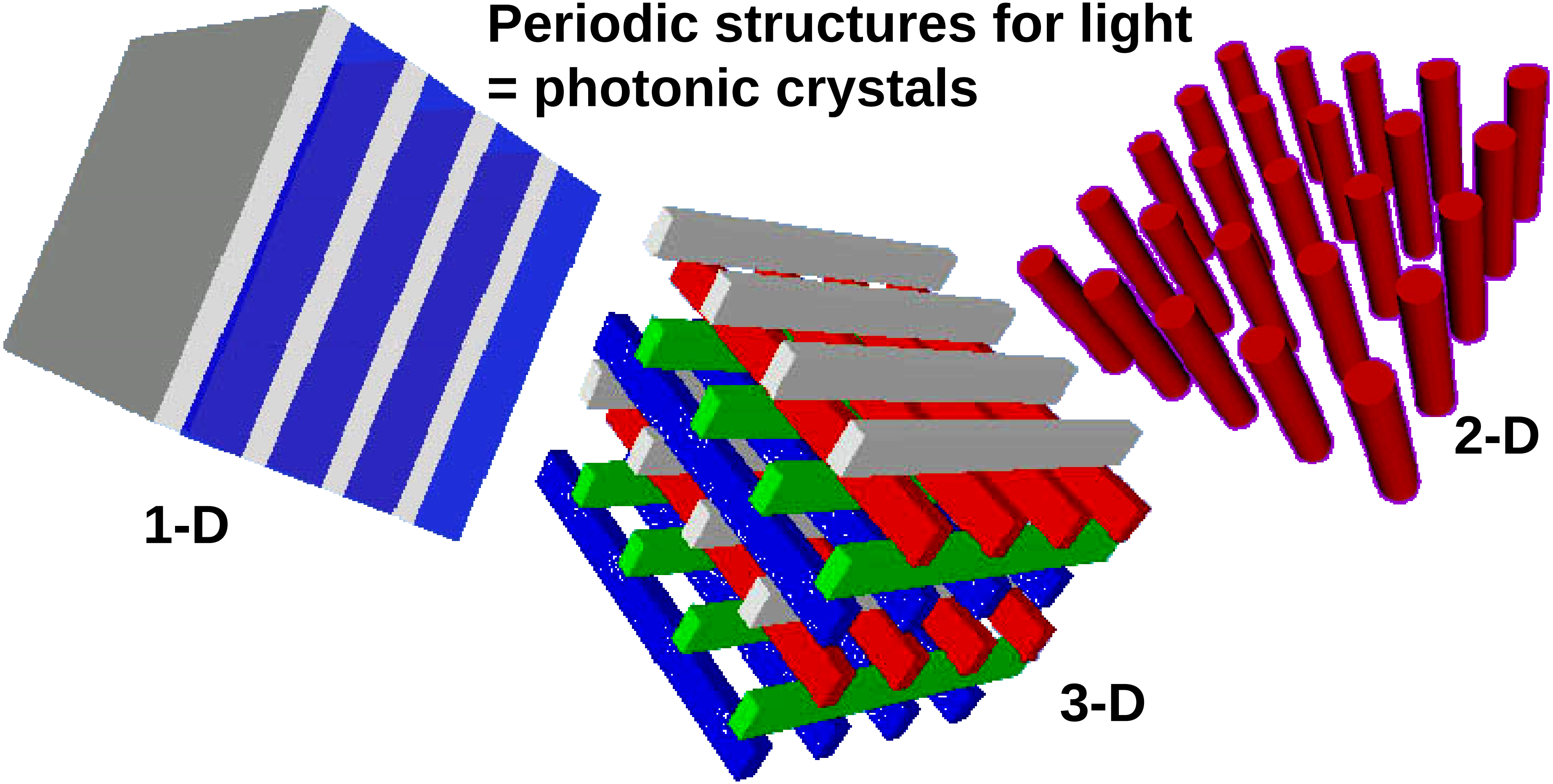
Photonic Band Gap (PBG)

Periodicity in more directions



Periodicity in more directions

Periodic structures for light
= photonic crystals



High refractive index contrast (larger than 2-to-1) needed for Full photonic band gap

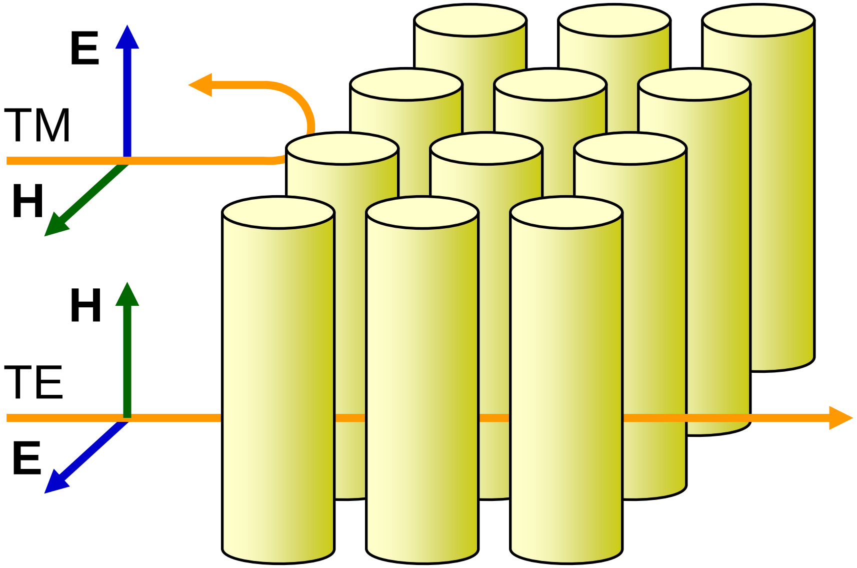
2-D photonic crystals

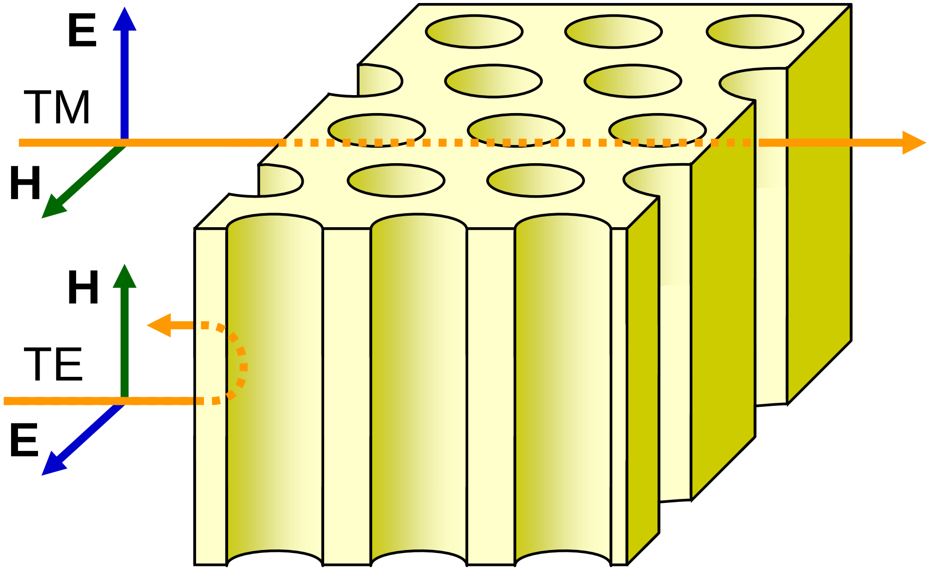
Pillars in air

- Only a photonic bandgap for light with the electric field parallel to the pillar axis
(= TM-polarisation)

holes in material

- Only a photonic bandgap for light with the electric field perpendicular to the pillar axis
(= TE-polarisation)





High refractive index contrast needed

A cage for light

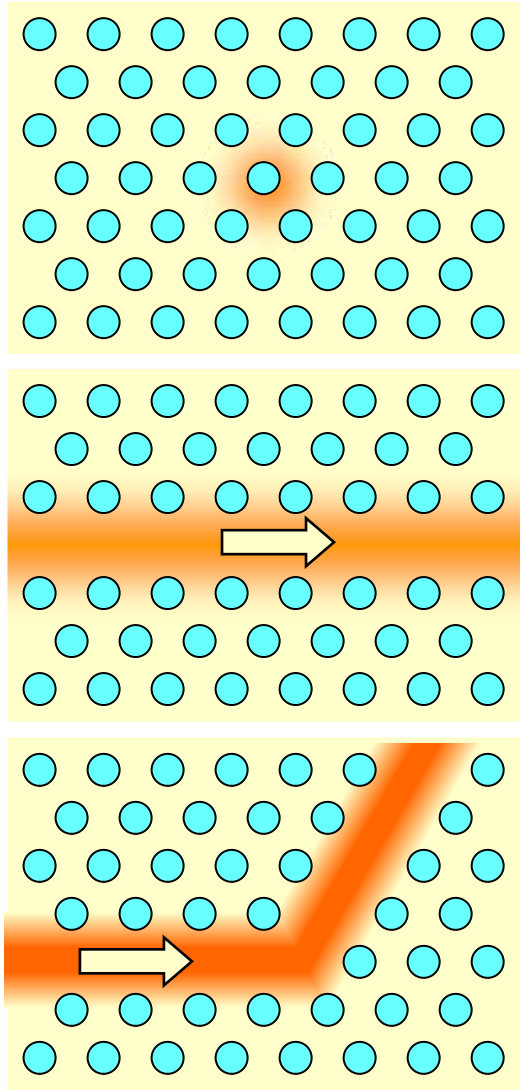
Perfect crystal with holes

- No light can exist there with a wavelength in the photonic band gap

Defect: change holes locally

- Around the defect light can exist with wavelengths in the PBG
- The light cannot propagate away because of the photonic crystal

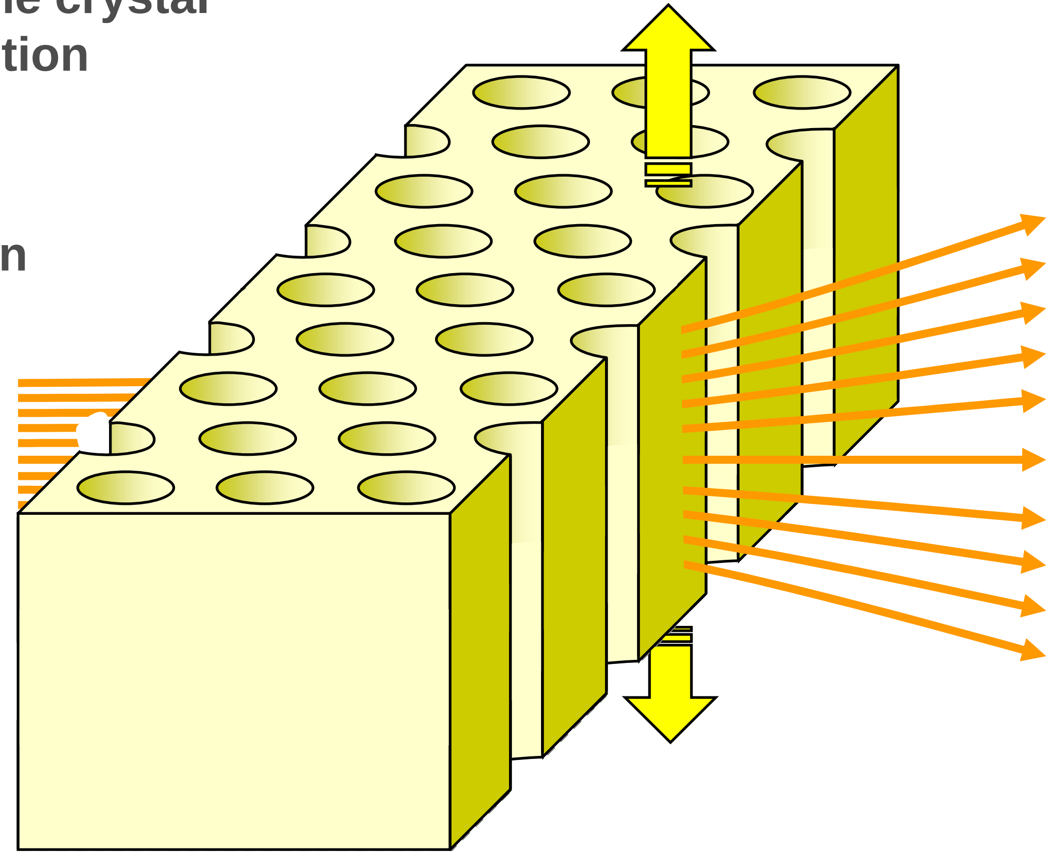
- e.g. in a line defect light has to follow the defect
  - = a waveguide
  - light cannot ‘miss the bend’



A waveguide in a 2-D crystal

Infinitely extended 2-D crystal

- remove one row of holes = waveguide
- Light is confined by the crystal in the horizontal direction
- Light can spread out in the vertical direction



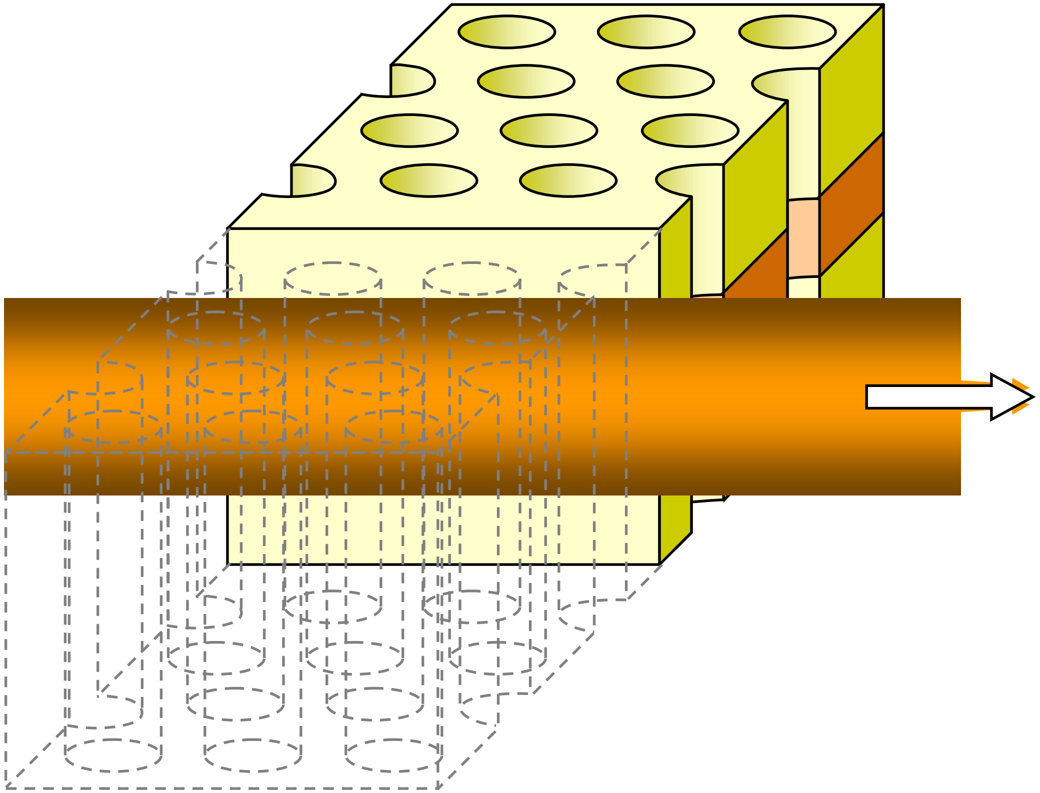
How do we confine the light vertically?

2-D crystal + slab waveguide

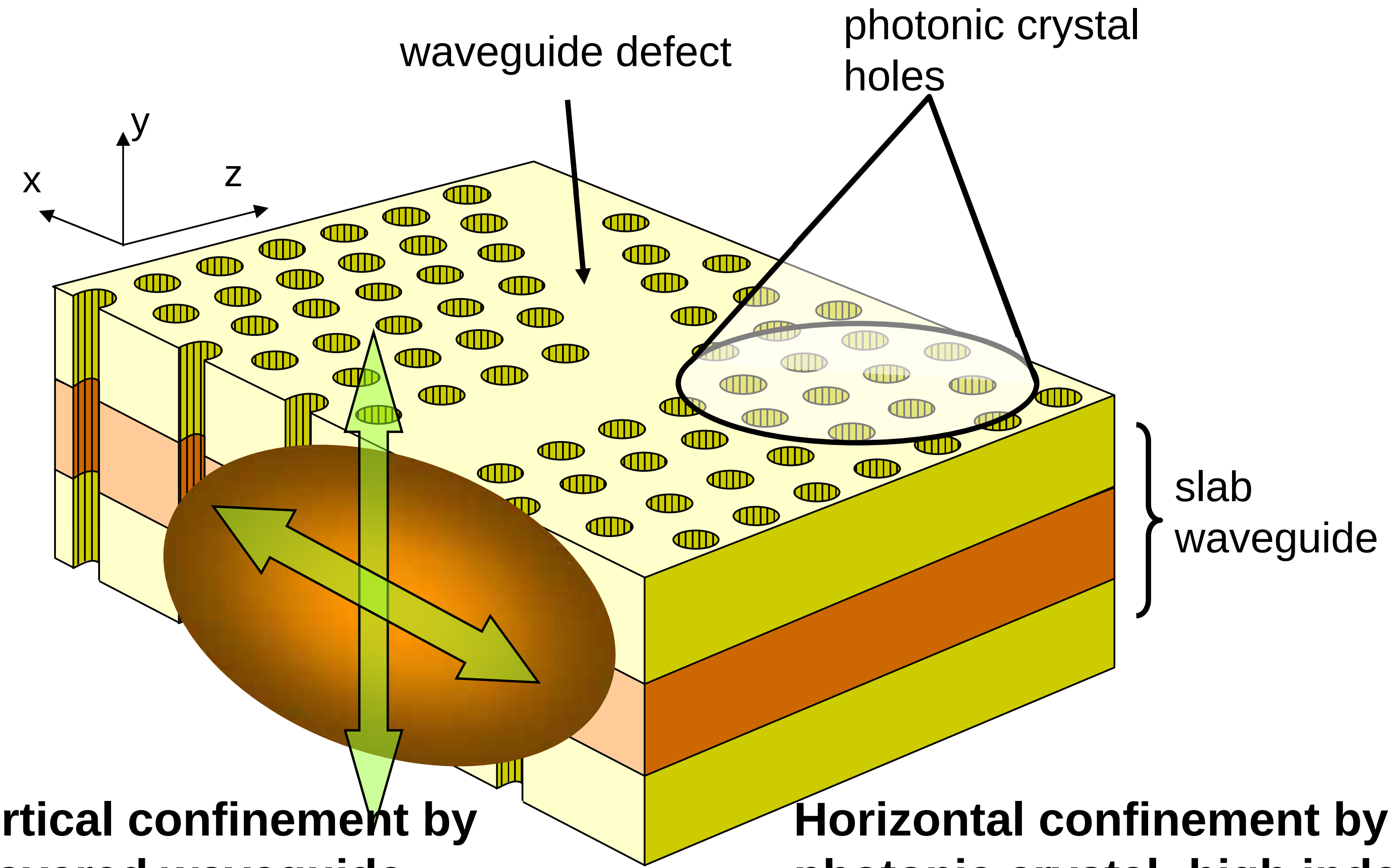
Solution: a layered waveguide

- Light is confined vertically by total internal reflection

- or more correct: a guided mode



Photonic Crystal Slab



Vertical confinement by a layered waveguide

Horizontal confinement by photonic crystal: high index contrast required

Overview of this presentation

Background on Photonics

- What’s the use?
- How does a waveguide work?
- Photonic Crystals
- SOI Nanophotonics

Which one to choose?

Why Silicon-on-Insulator?

UGent - I

- What ca
- Some key results

Worldwide State-of-the-art

Conclusion

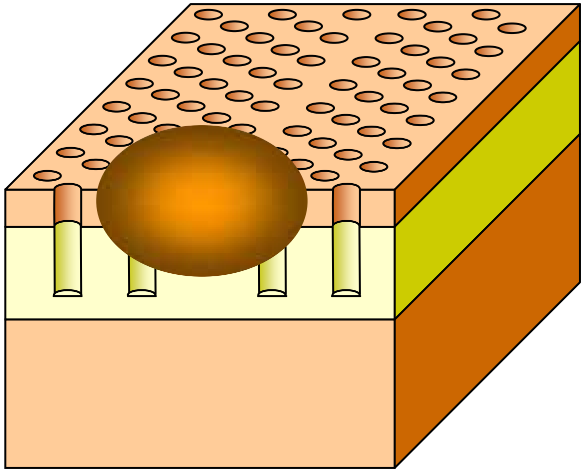
Nanophotonic Waveguides

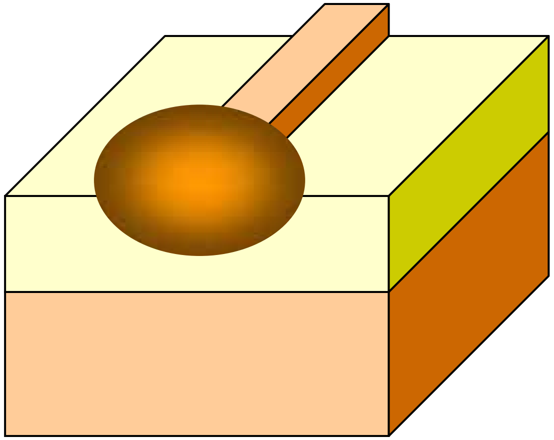
Photonic Crystals:

- In-plane: **Guiding by the photonic band gap**
- Vertical: Total internal reflection

Photonic Wires:

- In-plane: **Guiding by Total internal reflection**
- Vertical: total internal reflection





Both cases:

• Details : a few 100 nm

• Required precision: <10 nm

NANOPHOTONIC waveguides

Early days of Nanophotonics

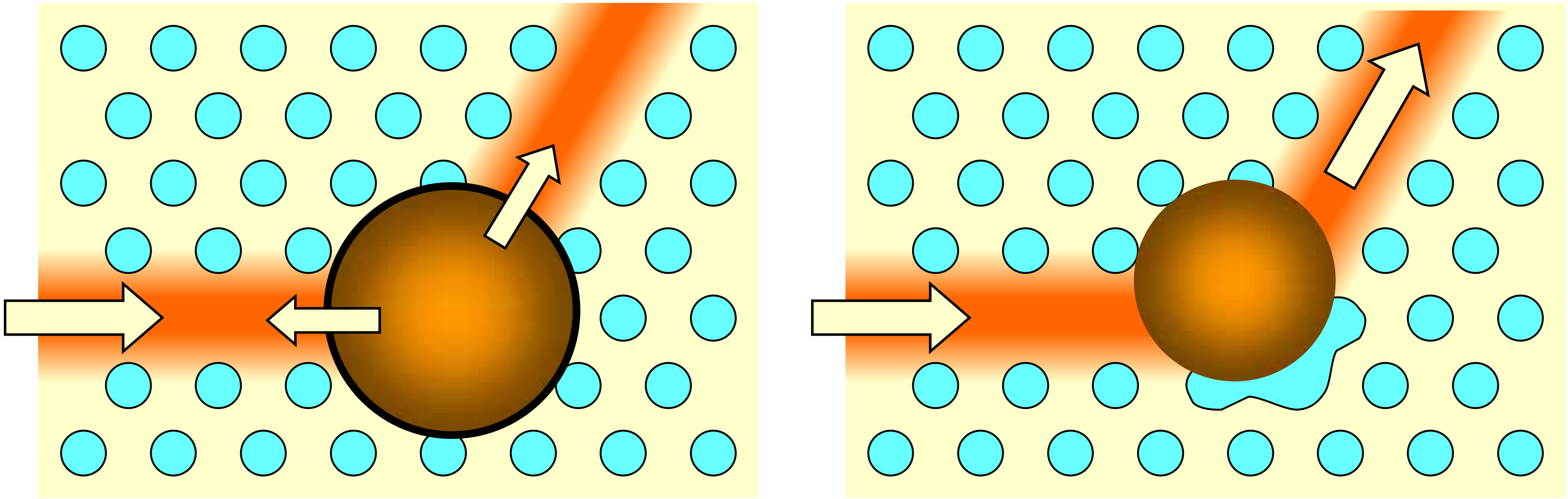
Photonic Crystals: not simple

In a simple bend:

- Out-of-plane scattering
- Backreflection

Solution: Optimise the bend geometry

(difficult heavy number crunching)



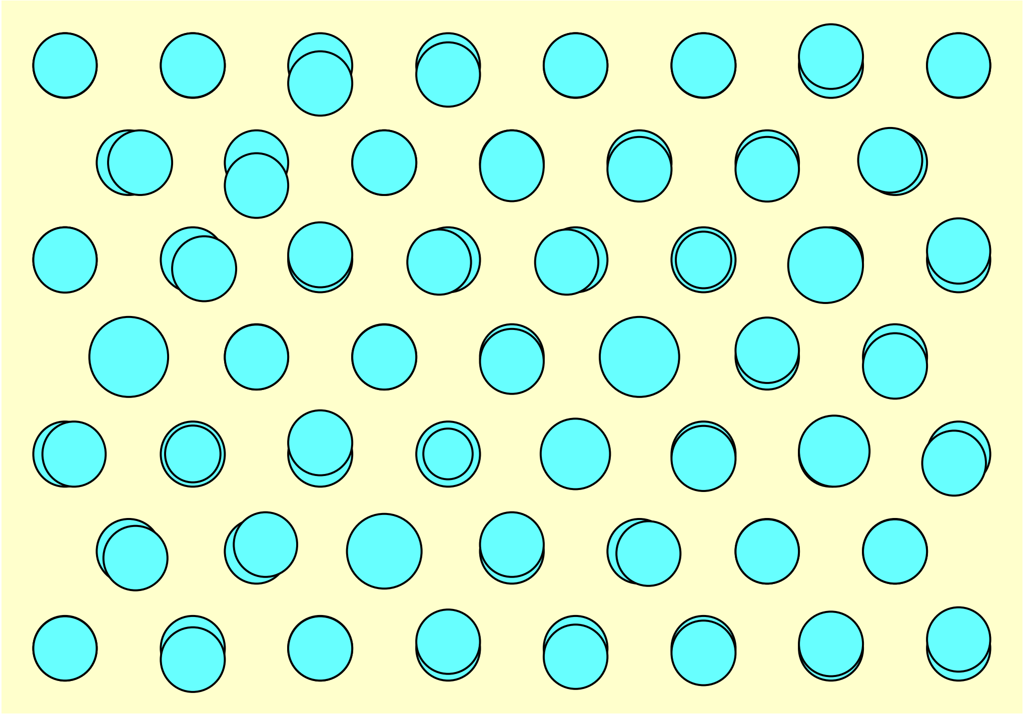
Photonic crystals are sensitive

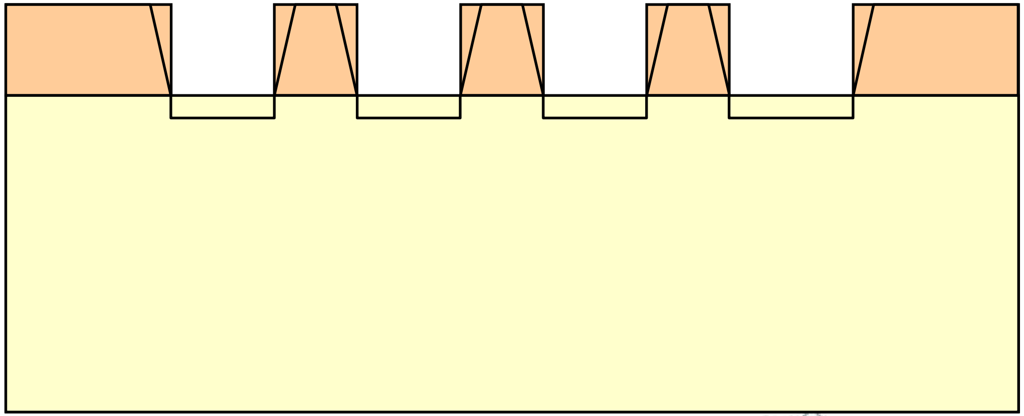
To disorder:

- roughness
- positioning
- hole size
- ...

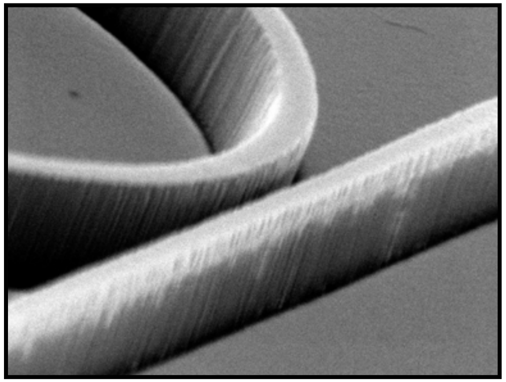
Etch geometry

- slanted sidewalls
- footing
- roughness





Scattering at roughness



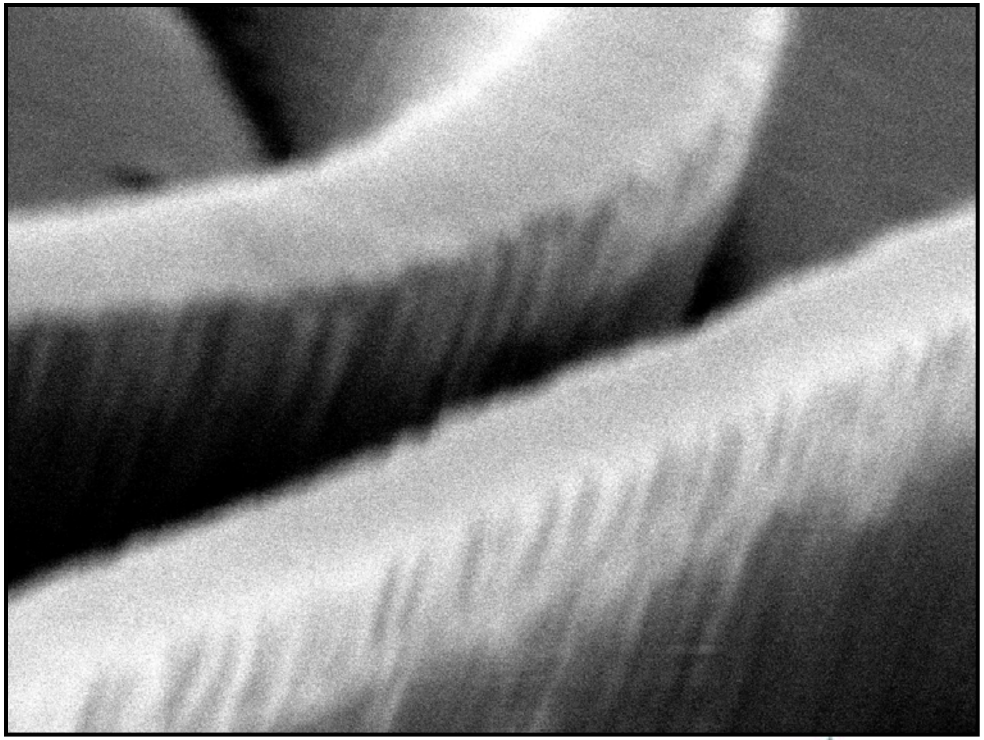
Imperfect fabrication

⇩

rough sidewalls

⇩

Light is being scattered out of the waveguide

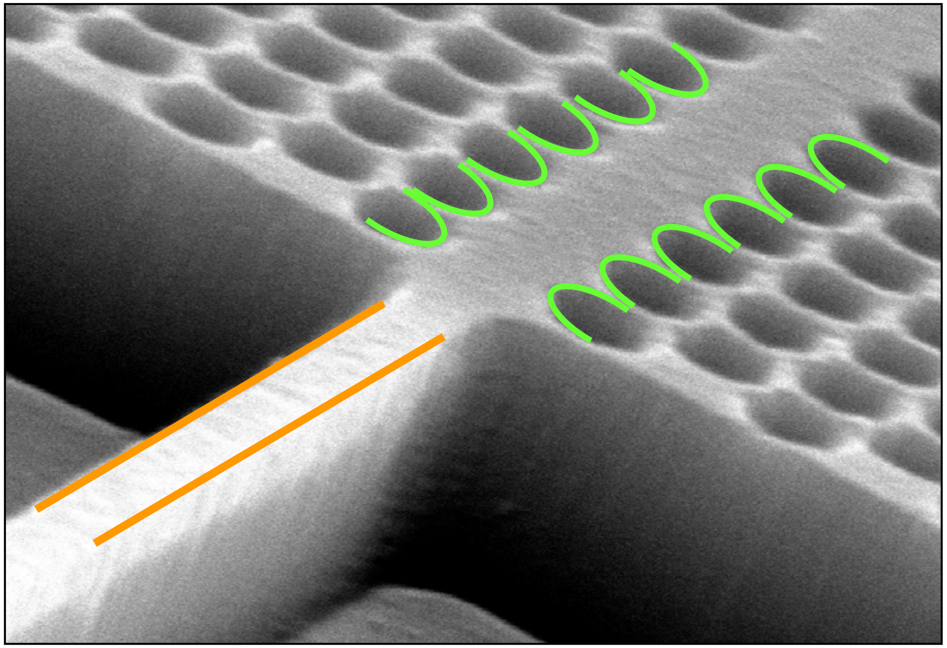


Scattering at roughness

Photonic Crystal: More sidewall surface than a photonic wire of equivalent length

↓

More sensitive to scattering at roughness



What are photonic crystals good at?

Inhibition of light

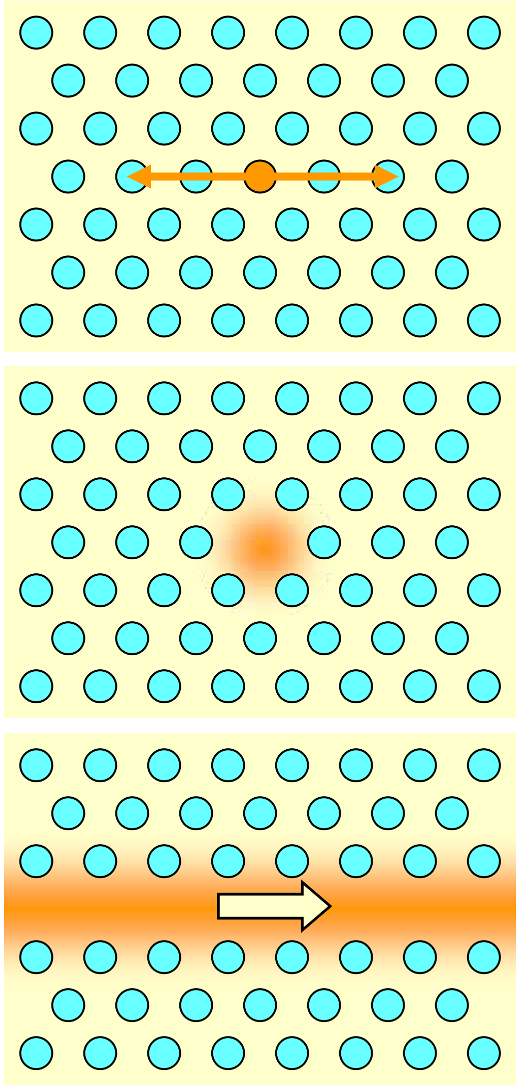
- change radiation patterns
- change light-matter interaction

Very tight confinement

- cubic wavelength cacvities

Strong dispersion

- Wavelength-dependent behaviour
- Slow light (IBM: c/300)

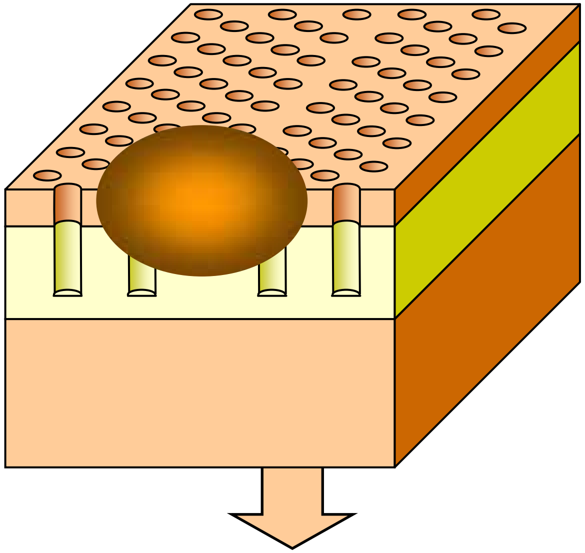


Compact functional elements

Nanophotonic Waveguides

Photonic crystals:

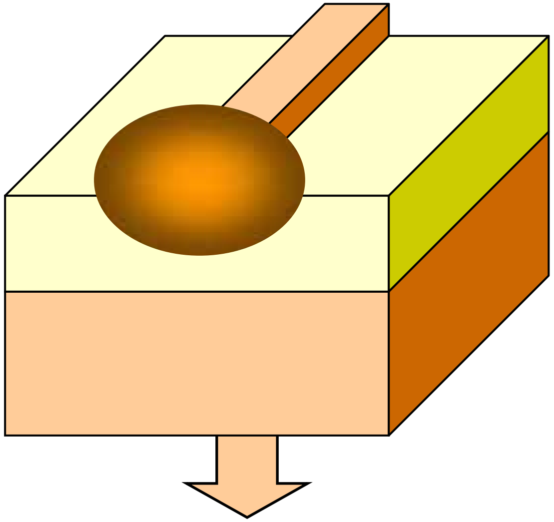
- Many possibilities
- Hard to design
- Losses



Use for compact functional elements

Photonic Wires:

- Simple
- Less loss (given good fabrication technology)



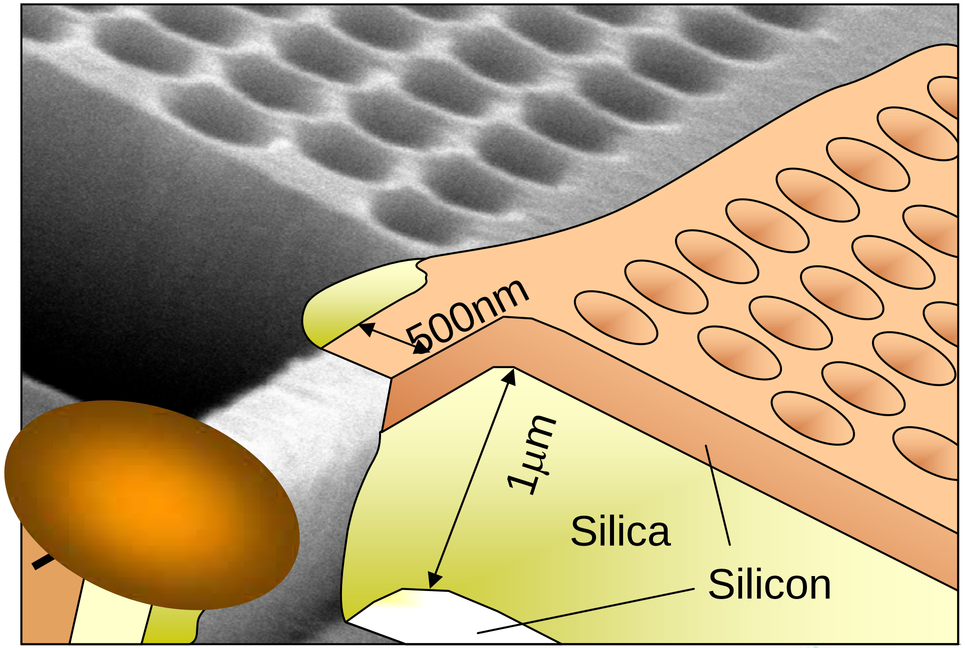
Use for waveguides (connections between elements)

Good fabrication technology needed

Silicon-on-Insulator

Why this material system?

- Transparent at telecom wavelengths (1550nm en 1300nm)
- High refractive index contrast
  - in-plane: 3.45 (Silicon) to 1.0 (air holes)
  - out-of-plane: 3.45 (Silicon) to 1.45 (silica)



Layer structure:
- 220nm Si
- 1000nm SiO_2

Silicon vs. other materials

Silicon

- Transparent at telecom
- High index contrast
- Native oxide
- Mature technology
- Electronics in same material

Guiding of light

Splitting, combining light

Wavelength selective functions

But

- No generation of light
- No detection of light
- Weak electrooptic effects

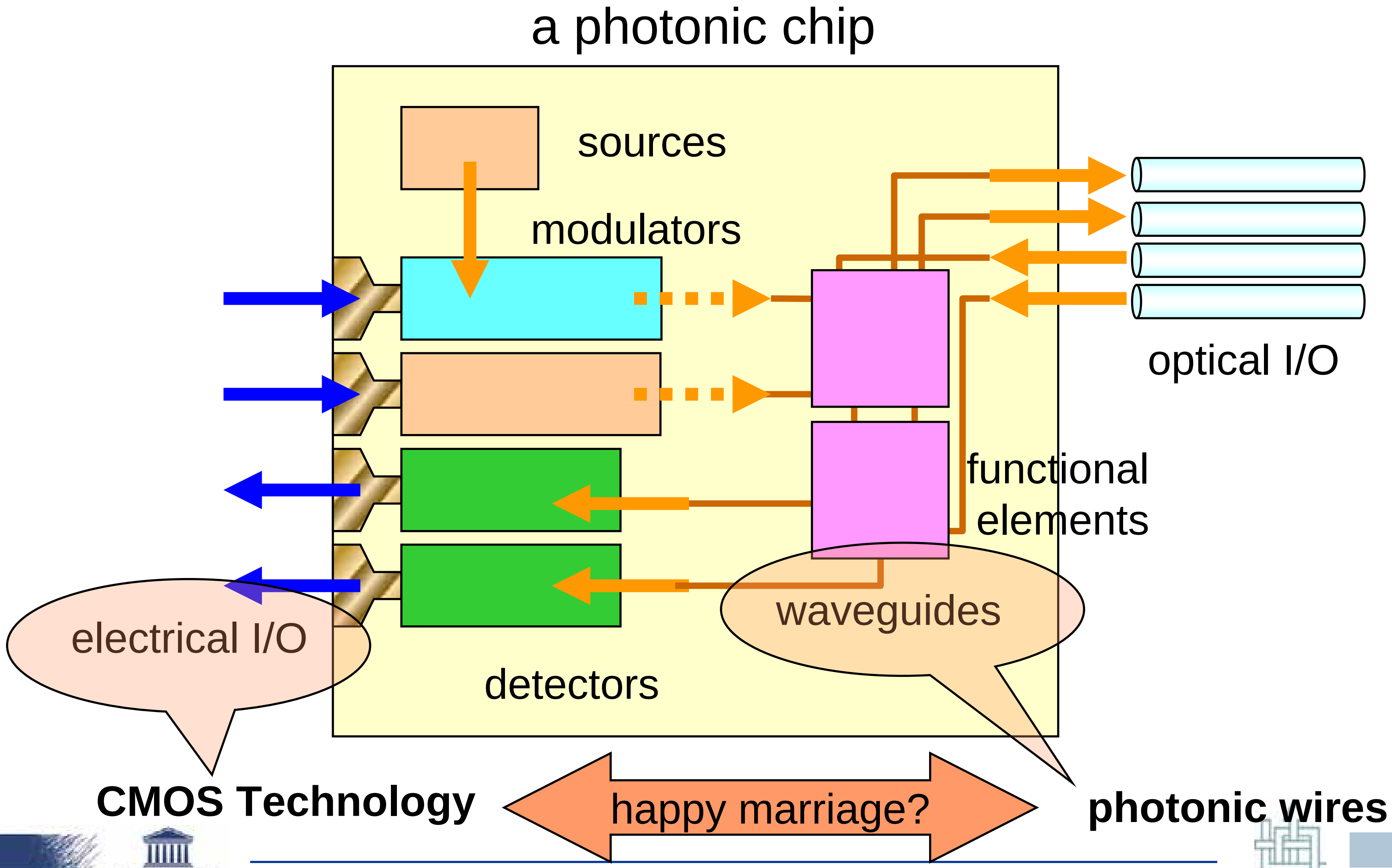
Sources, detectors

Amplification

Modulation, switching

Range of (incompatible) material systems:
GaAs, InP, $LiNbO_3$, doped SiO_2, ...

What is (quite) easy in Silicon?



CMOS Technology

photonic wires

CMOS-IC versus nanoPIC

CMOS

- Layered structures:
  - each layer one type of structures
  - separate litho + etch step per layer
- CD tolerances ~ 10%
- Alignment tolerances ~ 50nm (due to good design)
- No problems with roughness (for lines > 90nm)
- Bag of tricks optimized for each type of structure
- SOI: evolution to thin oxide for thermal dissipation

nanophotonic IC

- Planar structures
  - All types (photonic crystals, dense/isolated wires, ...) together
  - One litho for all
- CD tolerance ~ 10 → 1nm
- Alignment tolerances ~ 5nm (mode mismatch)
- Severe problems with roughness from 600nm down
- Use best 'common denominator' process
- SOI: thick oxide needed to prevent leaking of light

Overview of this presentation

Background on Photonics

- What’s the use?
- How does a waveguide work?
- Photonic Crystals
- SOI Nanophotonics

UGent - I

- What ca
- Some key results

How do we make it?
What are the problems?

Worldwide State-of-the-art

Conclusion

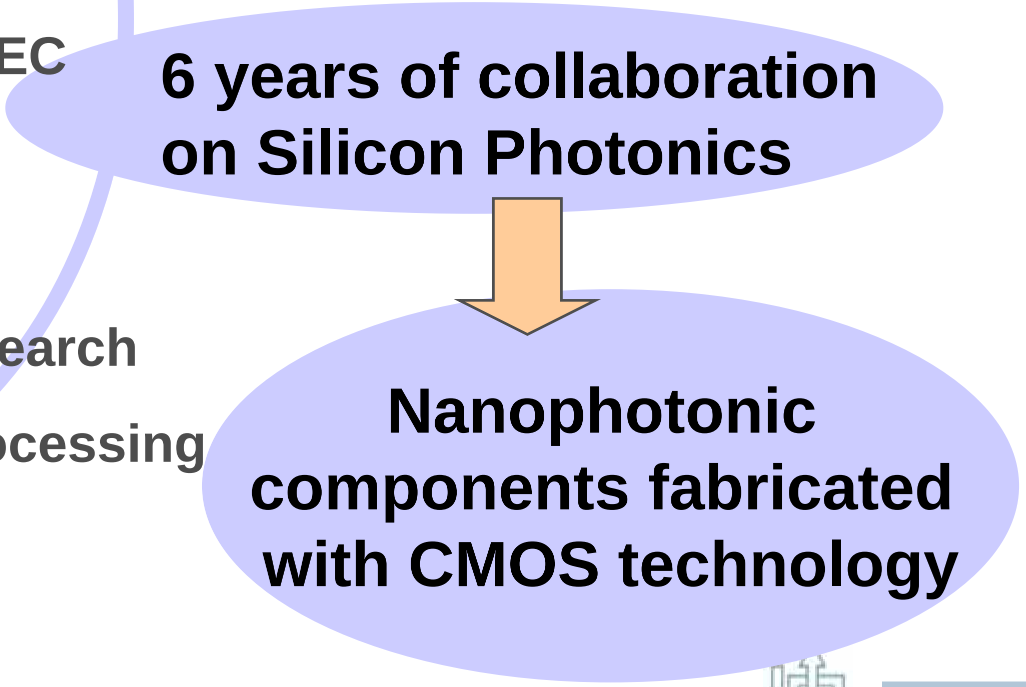
Silicon Photonics and UGent-IMEC

UGent – INTEC: Photonics Research Group

- 3 decades of photonics research
- Cleanroom facilities for III-V processing
- Photonics modelling
- Characterisation
- Associated Lab of IMEC

IMEC:

- Microelectronics Research
- Advanced Silicon Processing
- “Nanoelectronics”



6 years of collaboration on Silicon Photonics

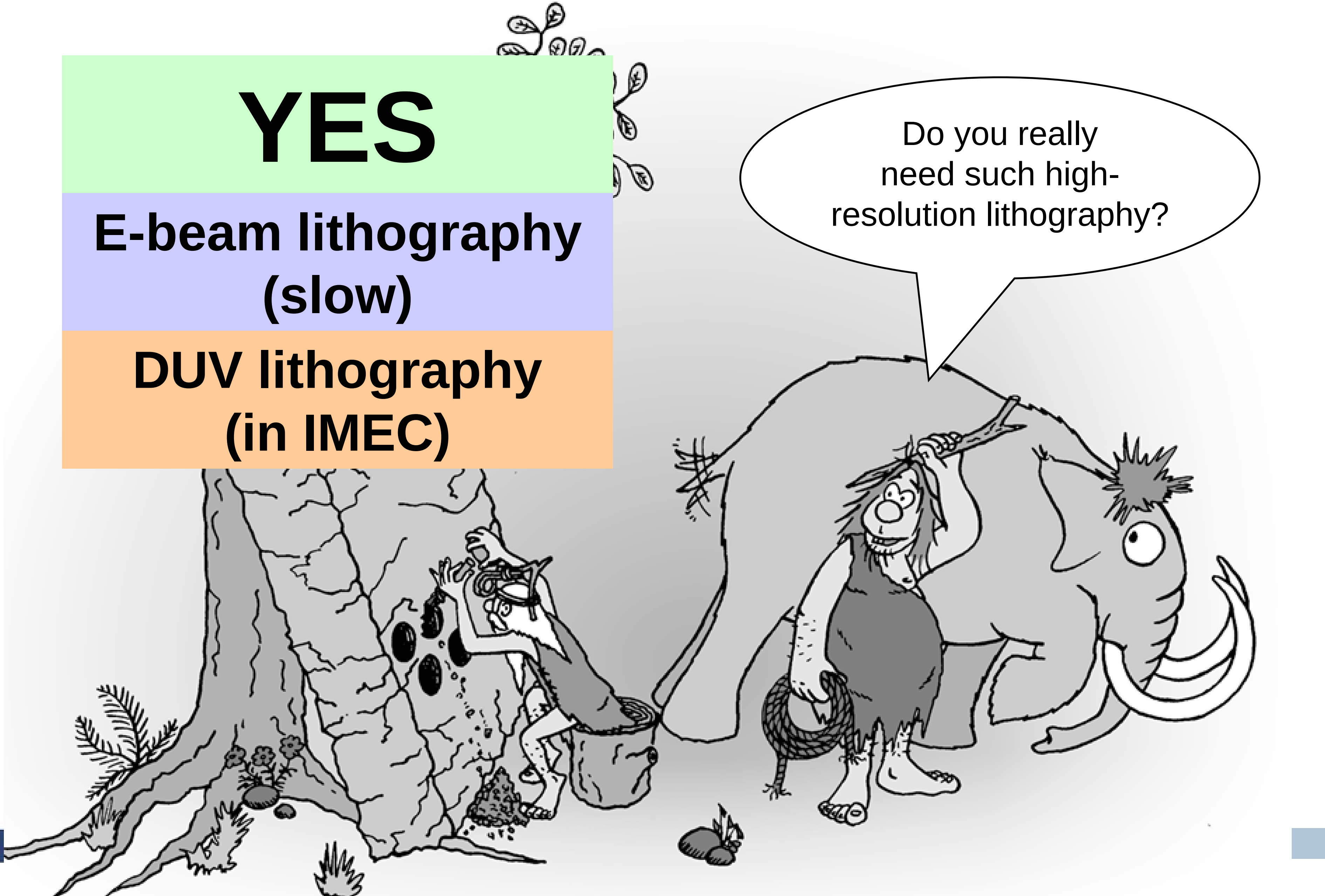
Nanophotonic components fabricated with CMOS technology

Litho-graphy = Stone-writing

YES

E-beam lithography (slow)

DUV lithography (in IMEC)

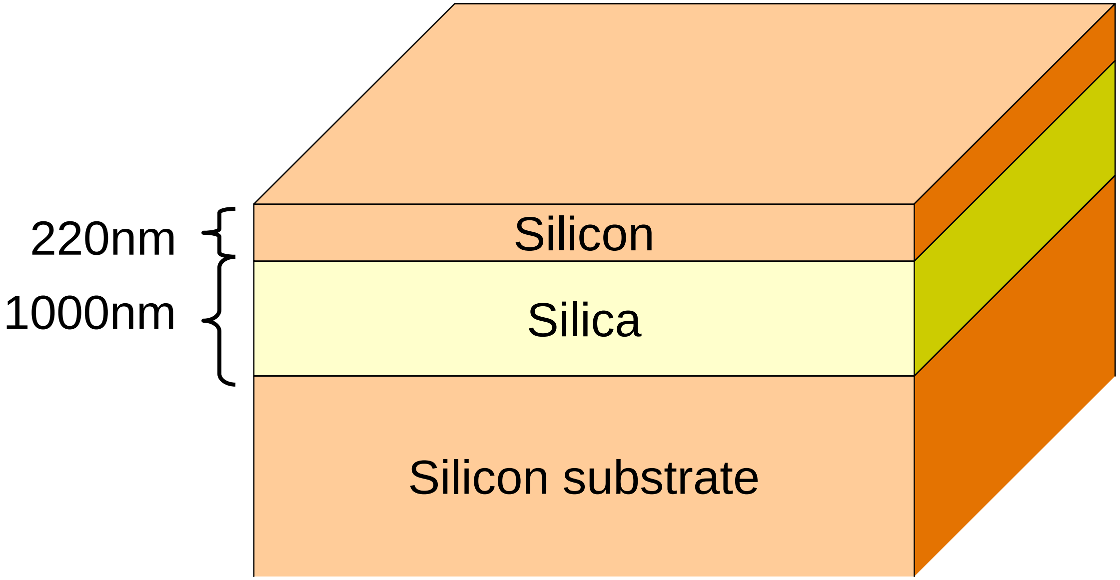


Step 1: A bare SOI wafer

Commercially purchased from SOITEC

Layer Structure

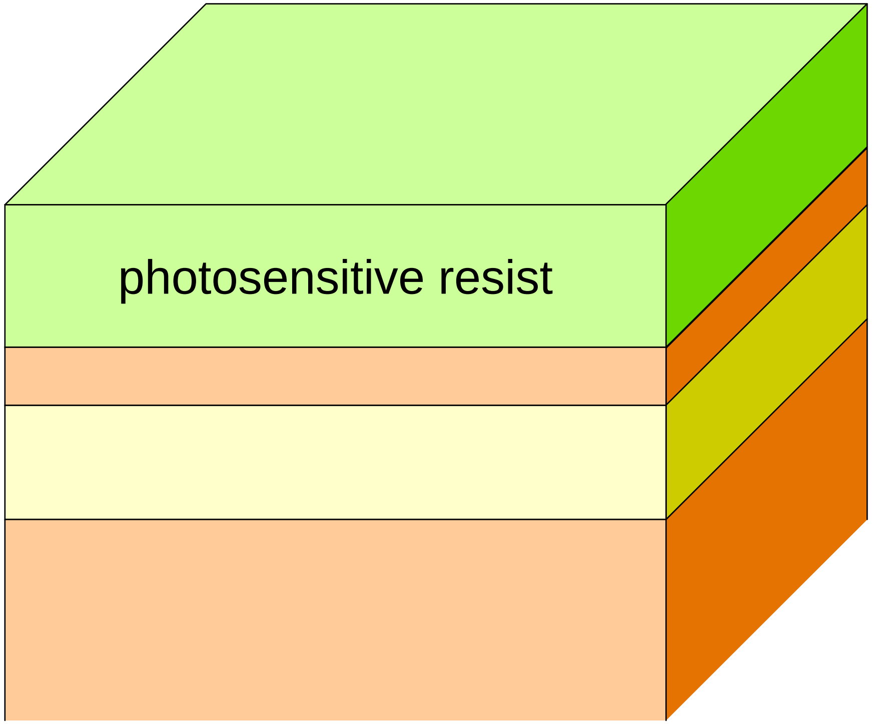
- **220nm Silicon (slightly p-doped)**
- **1000nm Silica buffer**



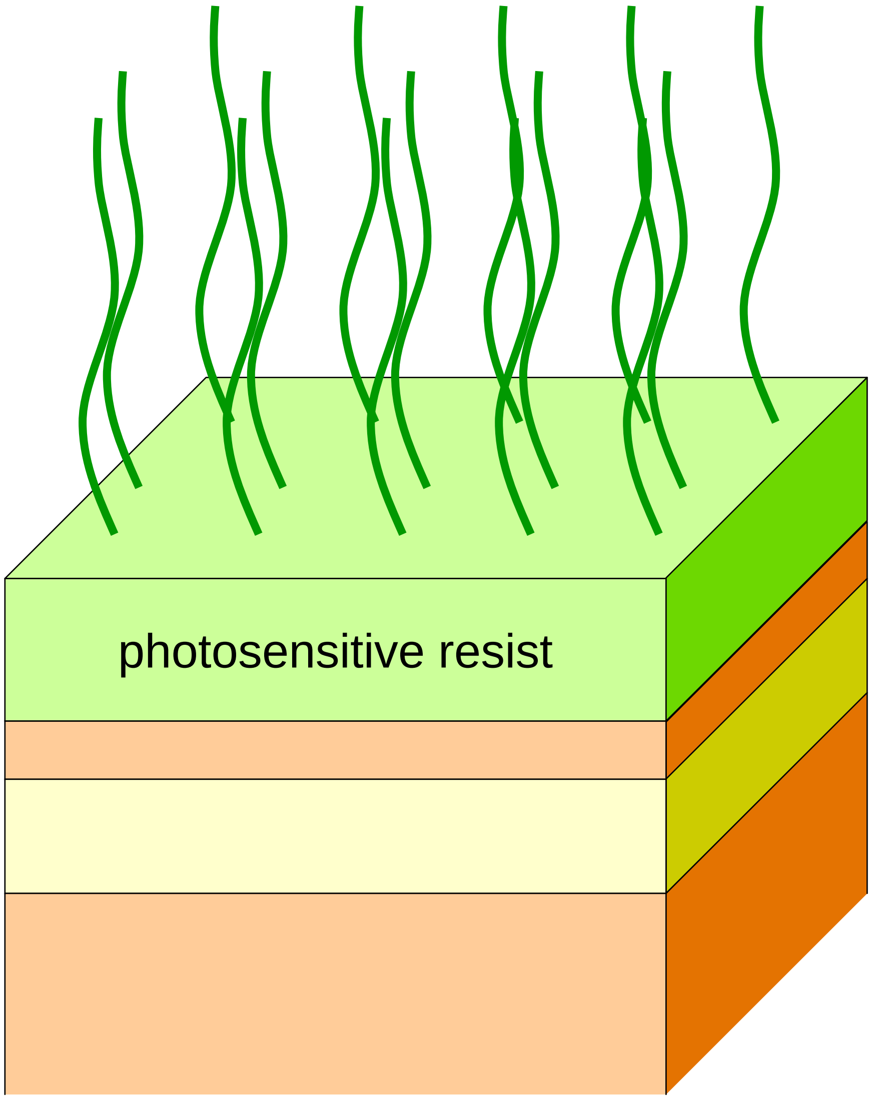
Step 2: Apply Photoresist

Photoresist

- Shipley UV3
- 800nm thick layer



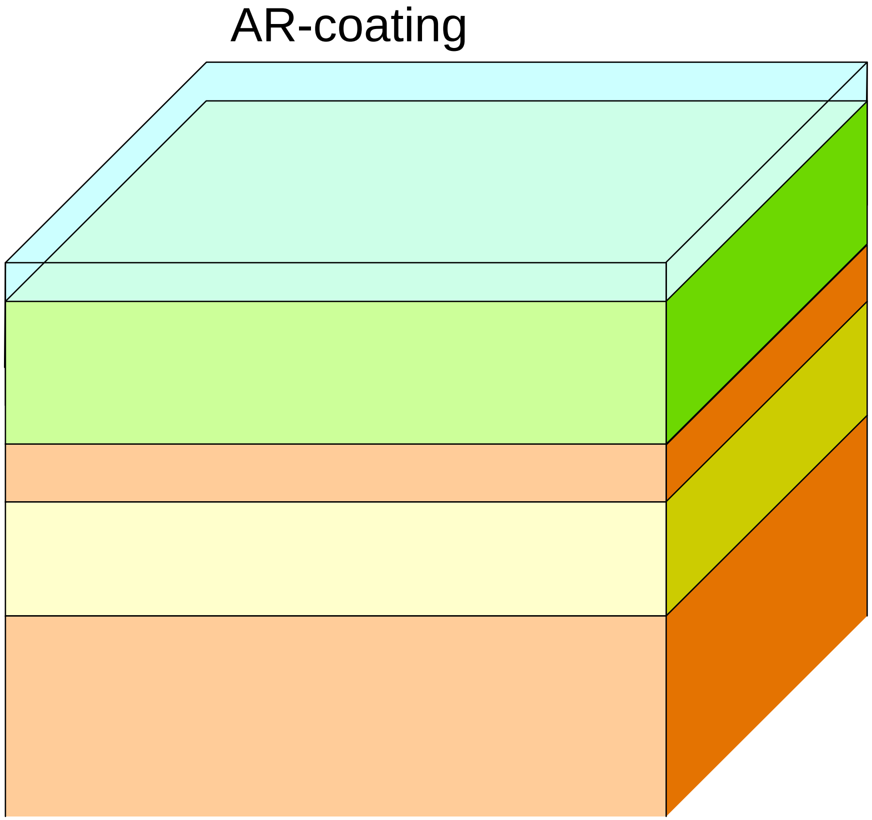
Step 3: Baking the photoresist



Step 4: Antireflective coating

AR coating

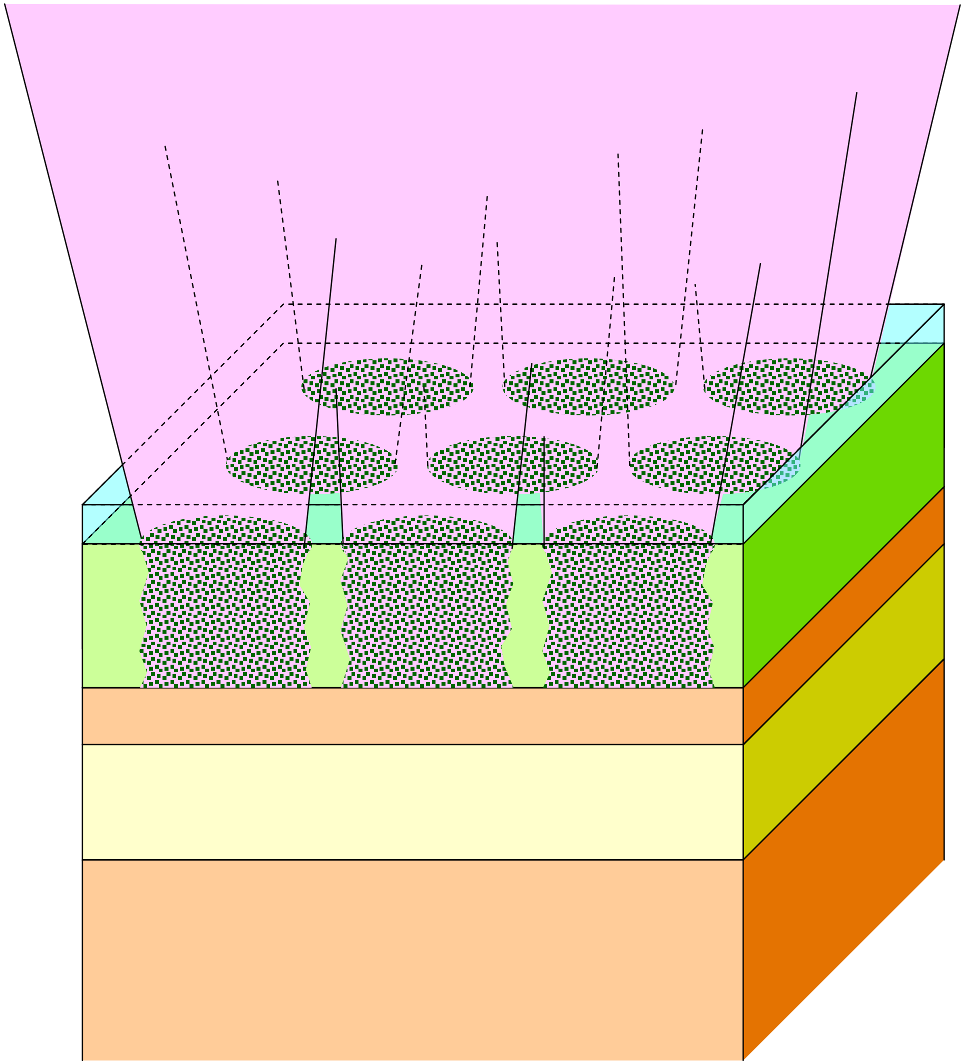
- to avoid reflections at the air-photoresist interface



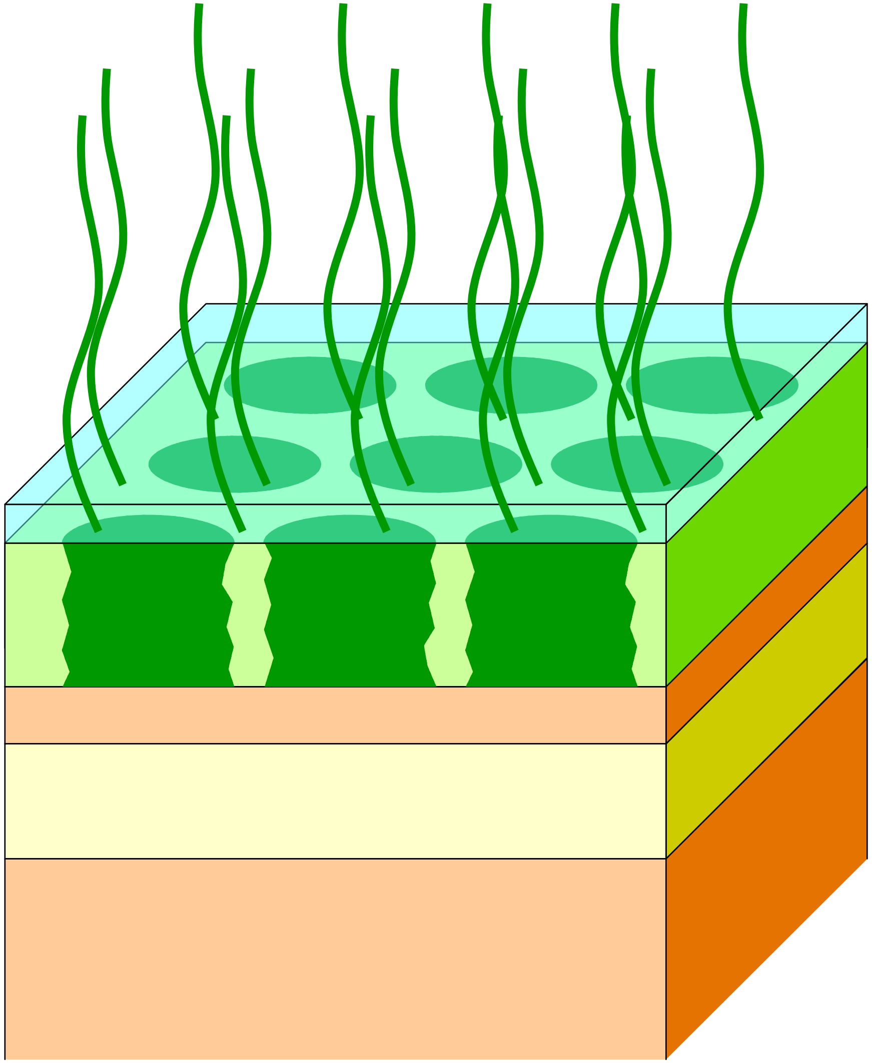
Step 5: Illumination

Deep UV Lithography

- ASML PAS5500/750
- KrF, 248nm
- 0.63 NA, 0.4σ
- Dose = 10-40 mJ/cm²



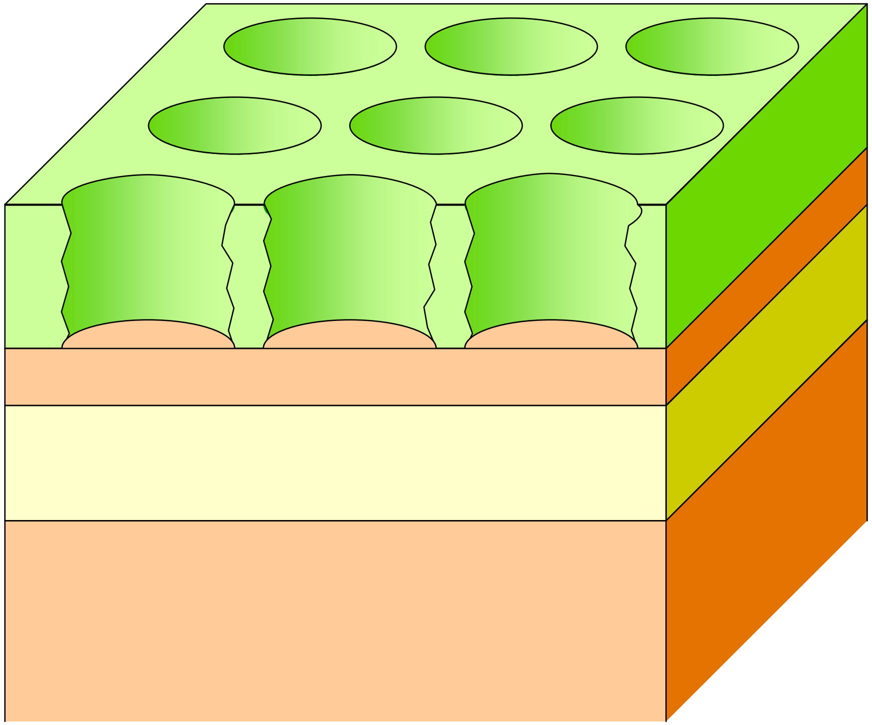
Step 6: Post-exposure bake



Step 7: Developing the resist

Unexposed areas become solid

Exposed areas are dissolved



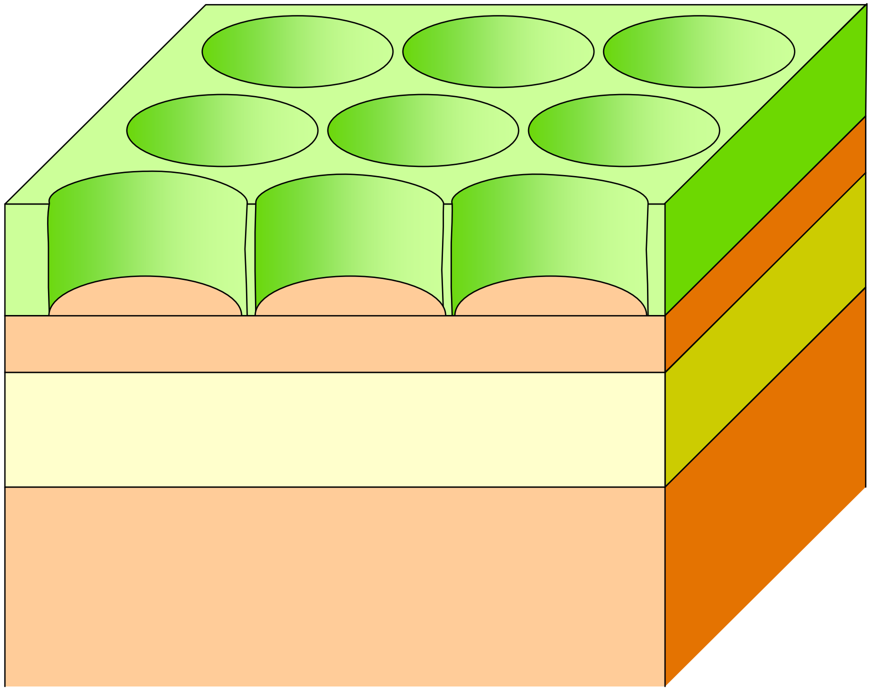
Step 8: Resist hardening

Goal

- reduce roughness
- compensate for litho-etch bias

But

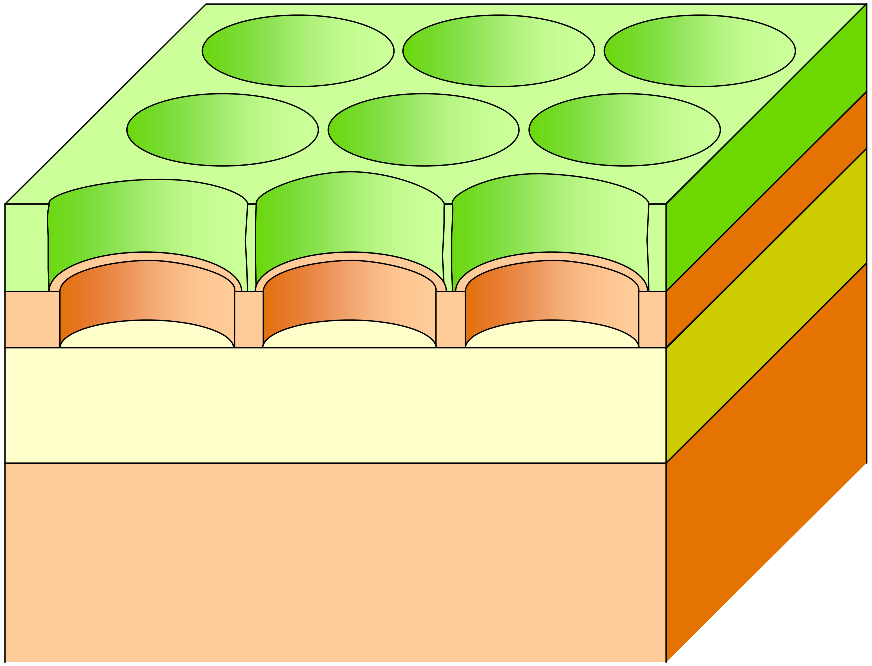
- “Consumes” litho process window



Step 9: Silicon etch

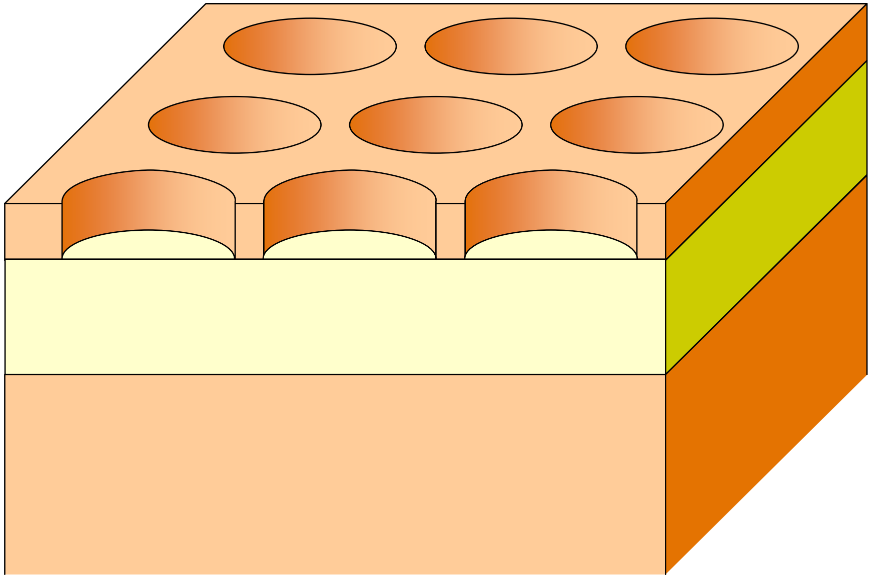
Etch

- LAM-POLY



Step 10: Strip the resist

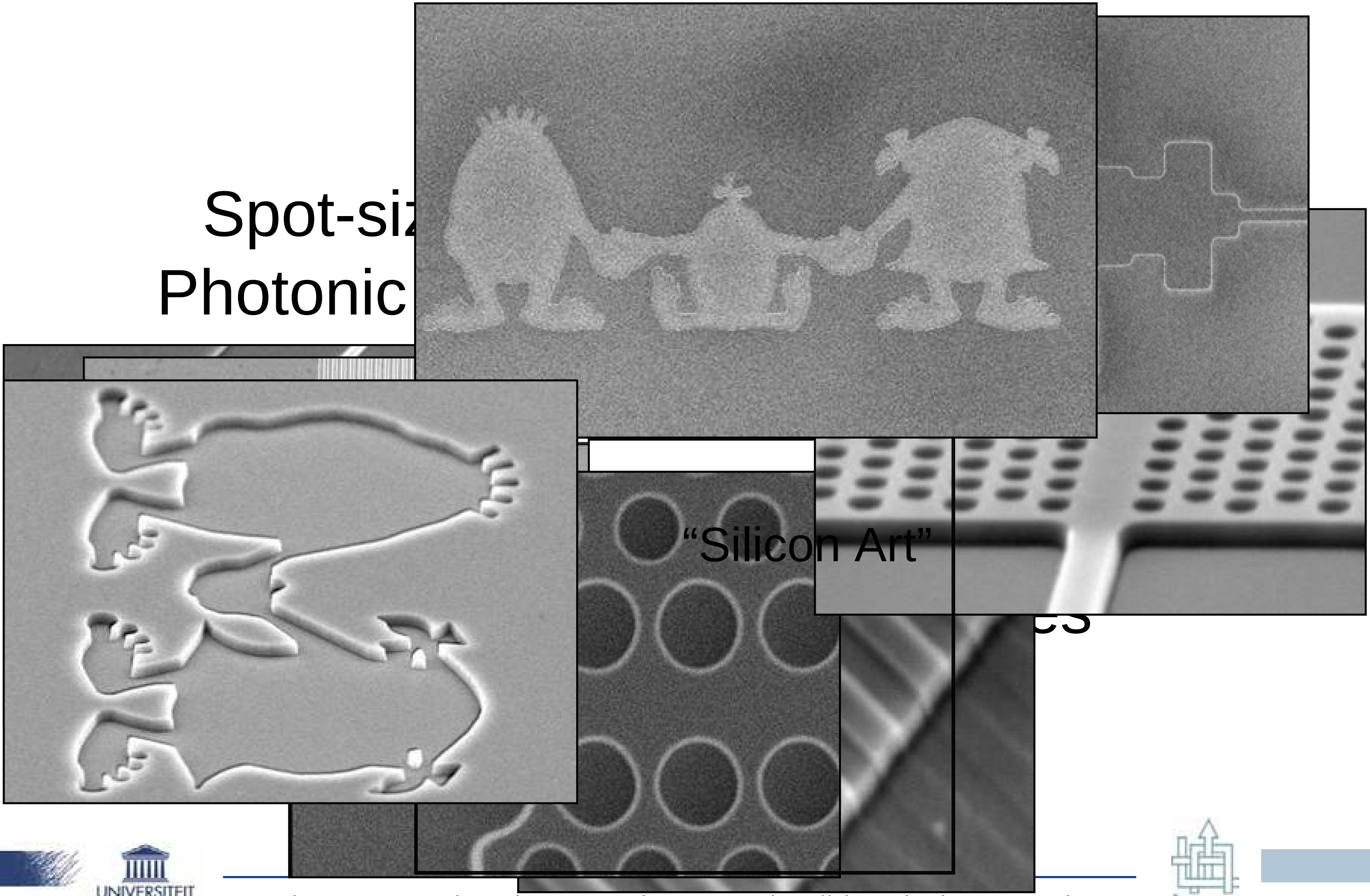
The residue of the photoresist is removed



What can we make?

Spot-siz

Photonic



“Silicon Art”

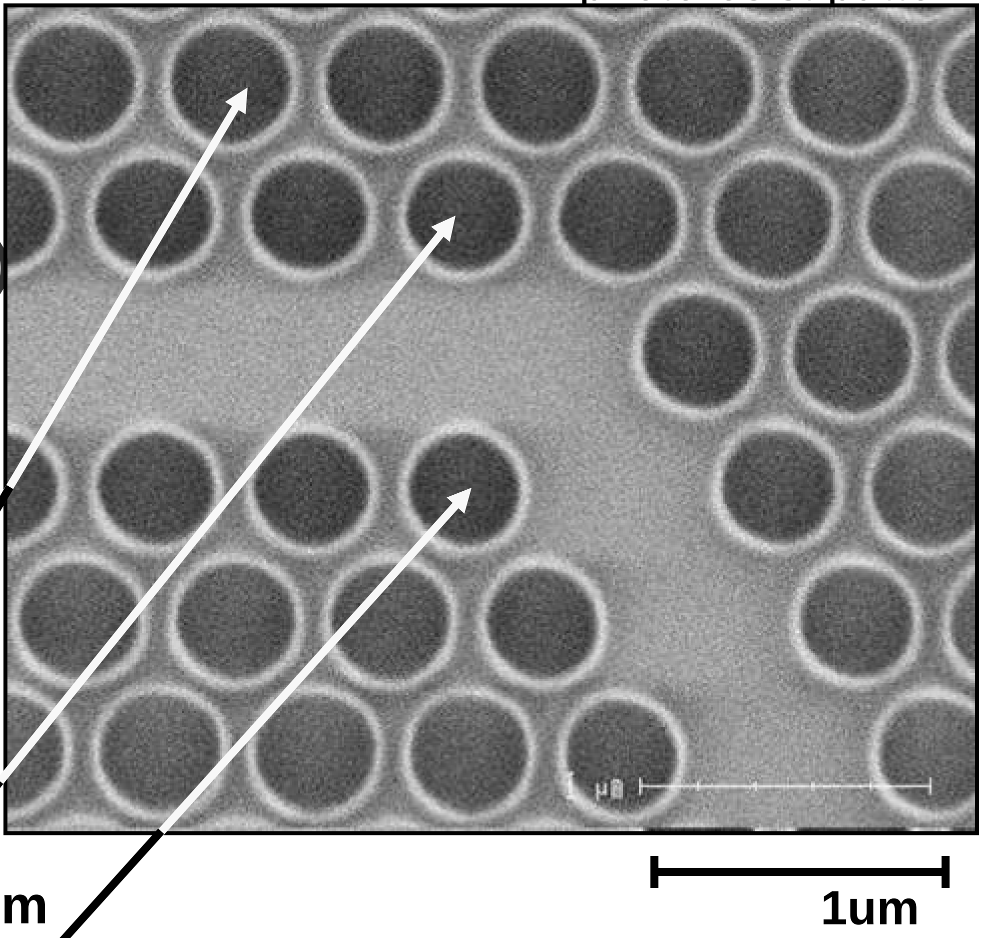
es

Problem: Proximity effects

Problem:

Holes near edges differ from holes in the bulk (while they should be identical!)

photoresist pattern



hole in the bulk = 420nm

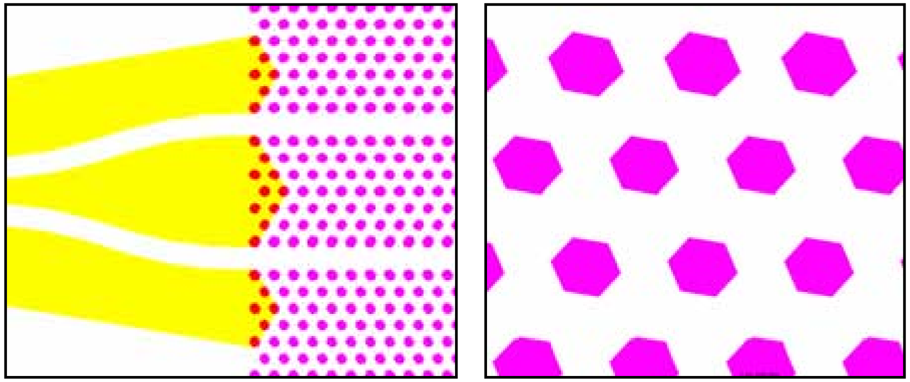
Hole on the edge = 380nm

Hole on the corner = 350nm

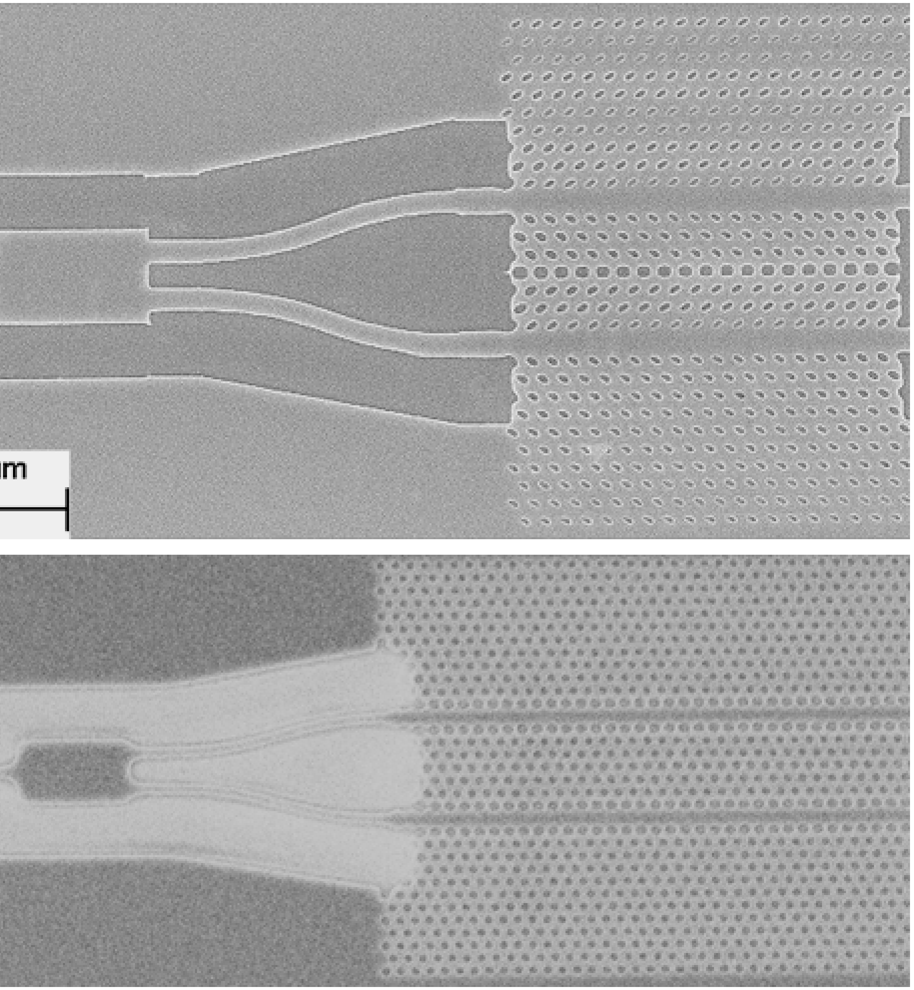
Deep UV vs. E-Beam

Fabrication comparison

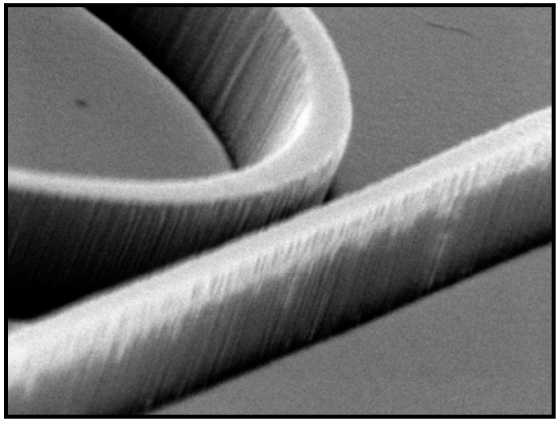
- Design: Elliptical holes



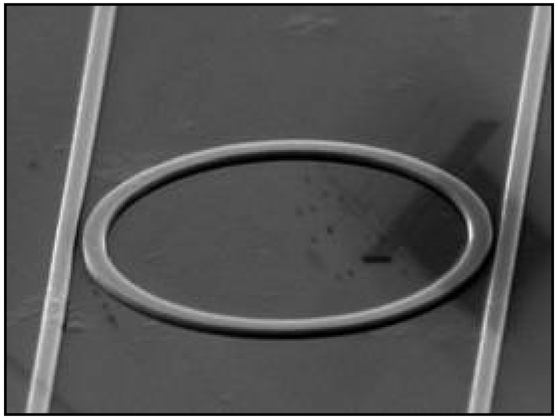
- E-beam lithography: holes are elliptical
- Deep UV lithography: holes end up round



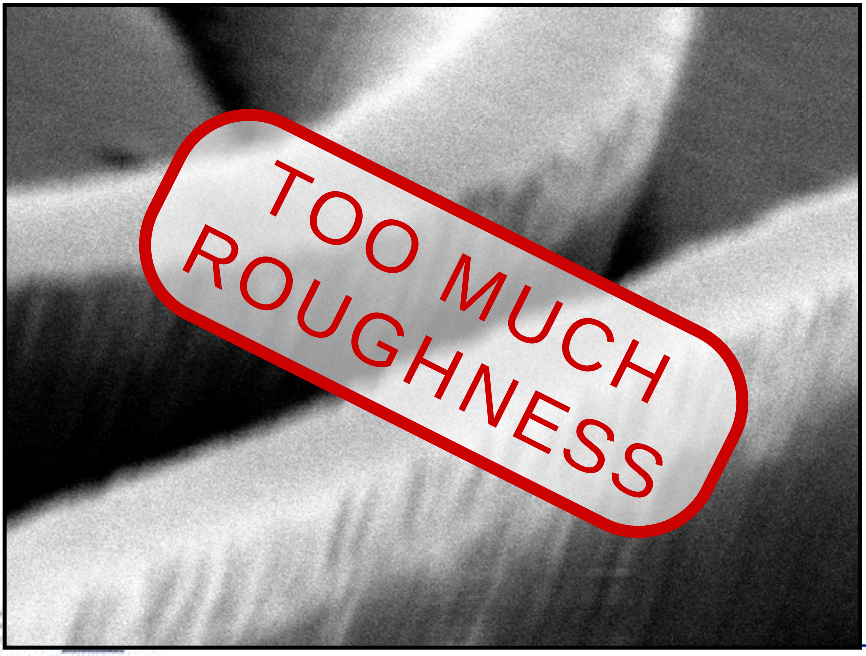
Sidewall roughness



Deep etching: Silicon + Oxide

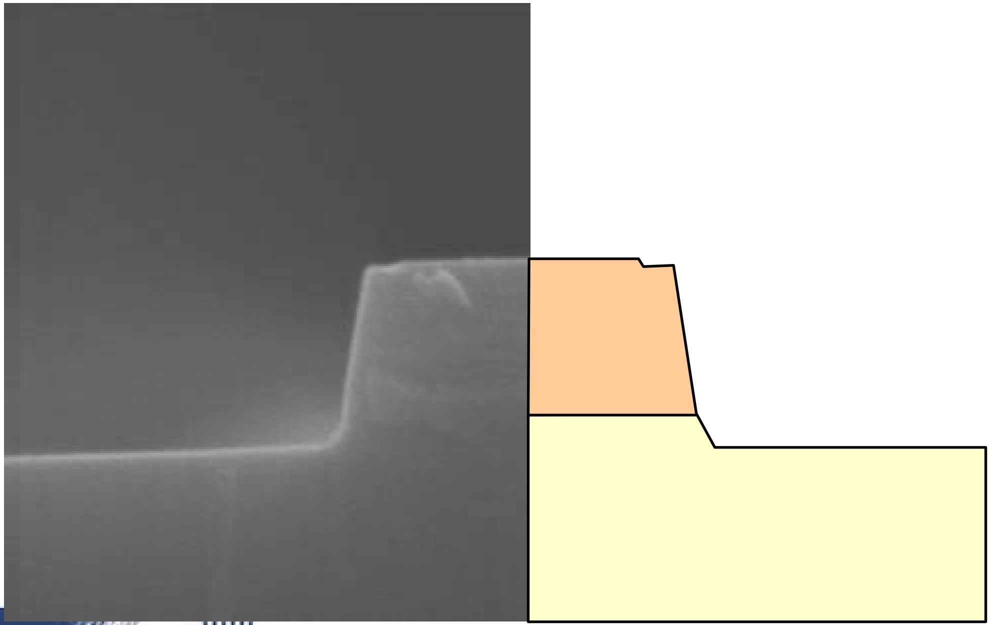


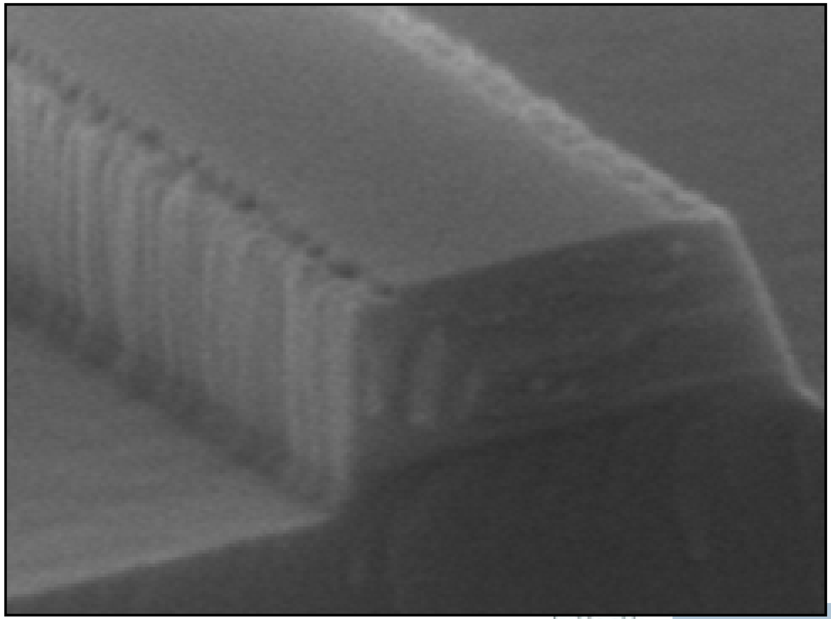
Silicon Only etching



Still quite rough

- still sidewall roughness
- sidewall slope 8° ($W_{top} – W_{bottom}$ > 60nm)
- (unwanted) etch in the oxide (~20nm)
- damage at top edges (resist breakthrough?)





Overview of this presentation

Background on Photonics

- What's the use?
- How does a waveguide work?
- Photonic Crystals
- SOI Nanophoto

UGent - IMEC a

- What can we d
- Some key resu

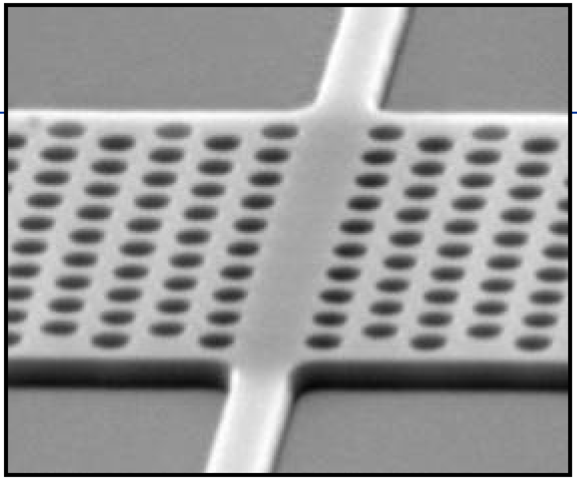
Worldwide Stat

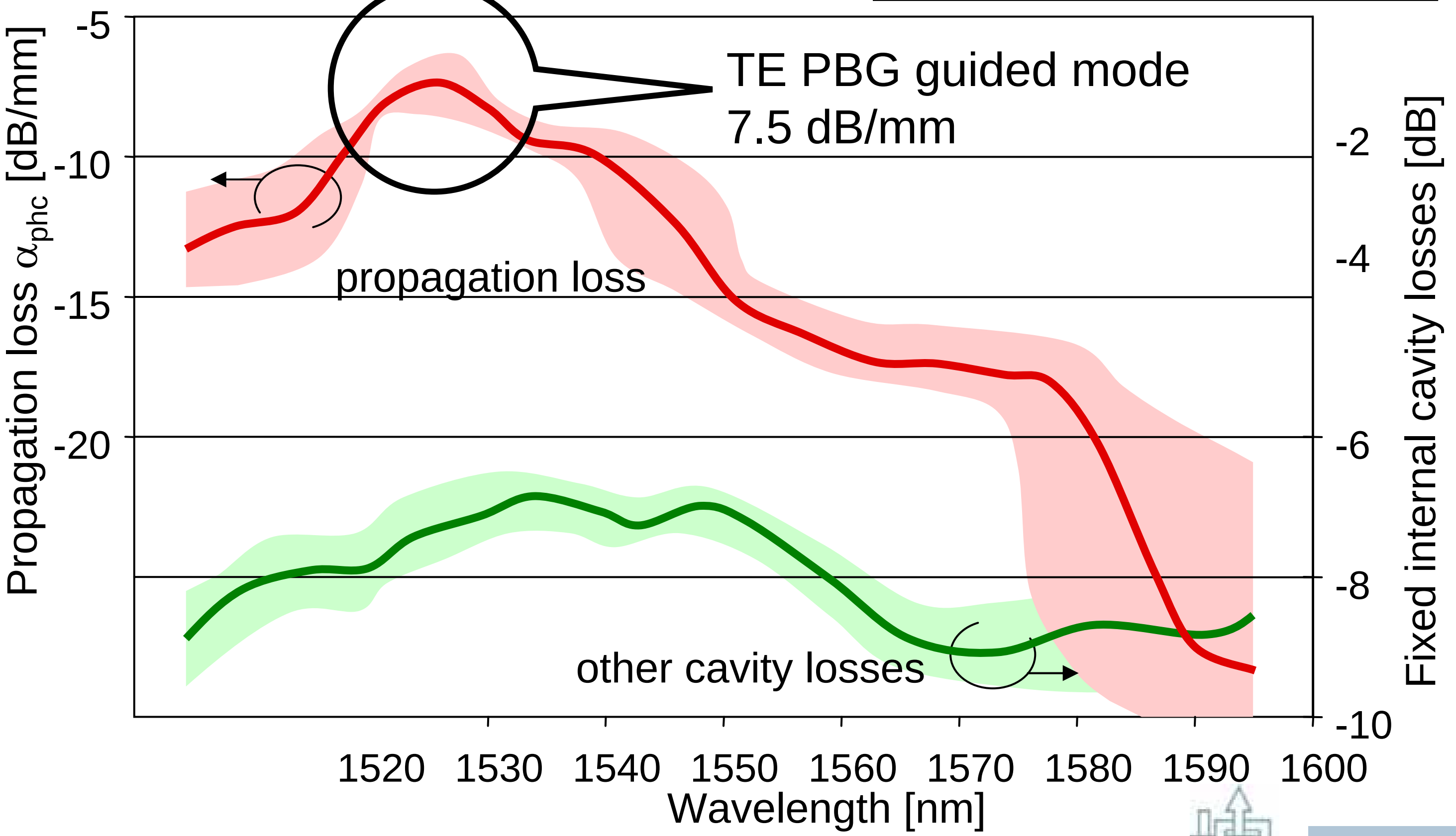
Conclusion

Photonic Crystals
Photonic wires
Wavelength filters
Fibre coupling

W1 PhC waveguide

- Pitch = 500nm
- Hole diameter = 320nm
- Silicon-only etch
- TE measurement



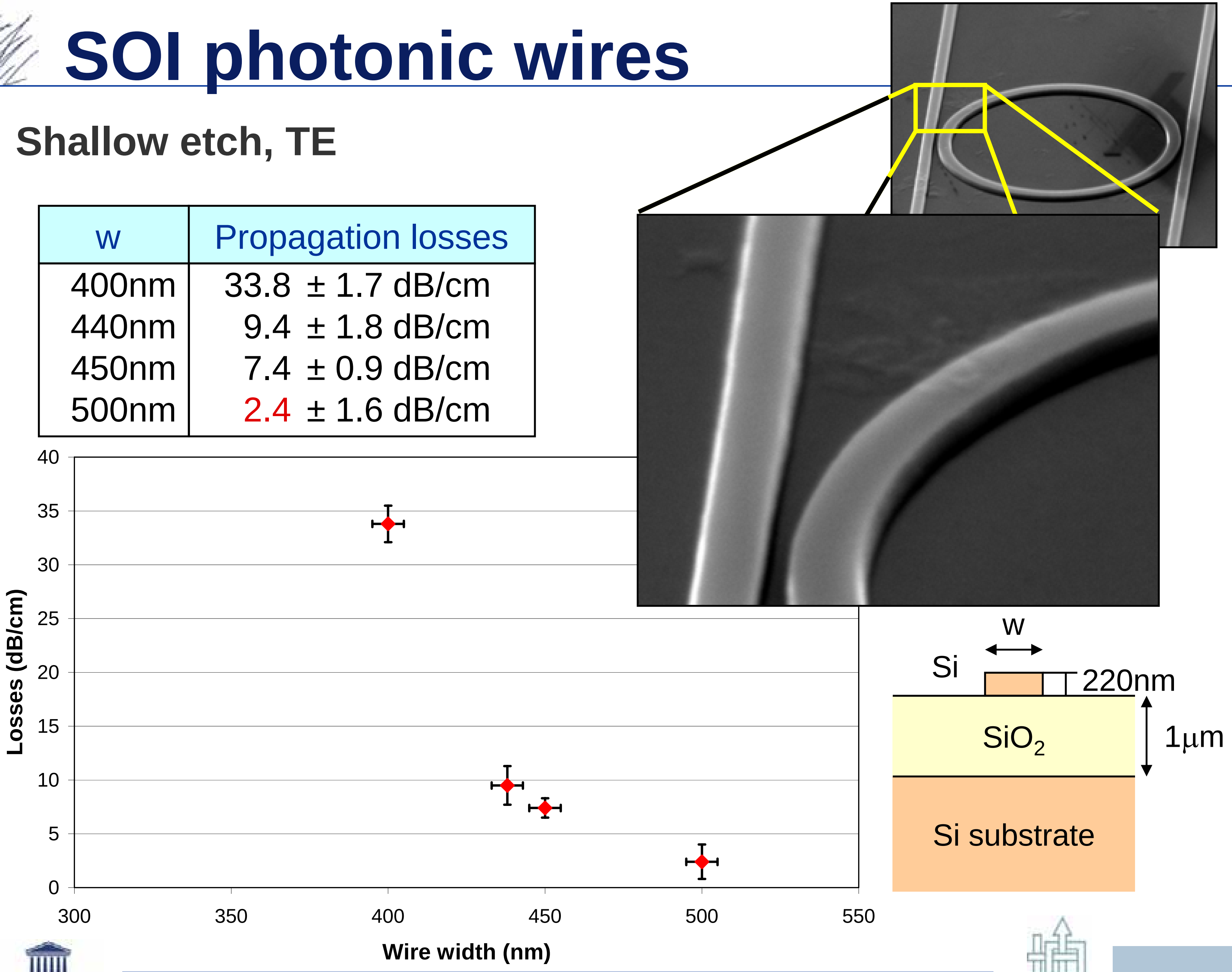


TE PBG guided mode
7.5 dB/mm

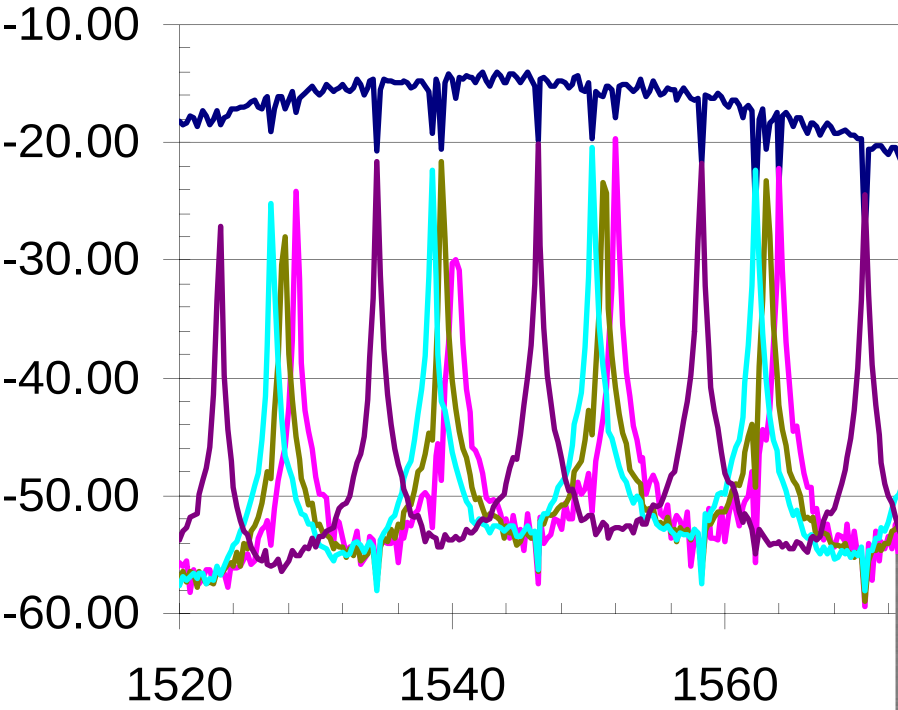
SOI photonic wires

Shallow etch, TE

w	Propagation losses
400nm	33.8 ± 1.7 dB/cm
440nm	9.4 ± 1.8 dB/cm
450nm	7.4 ± 0.9 dB/cm
500nm	2.4 ± 1.6 dB/cm

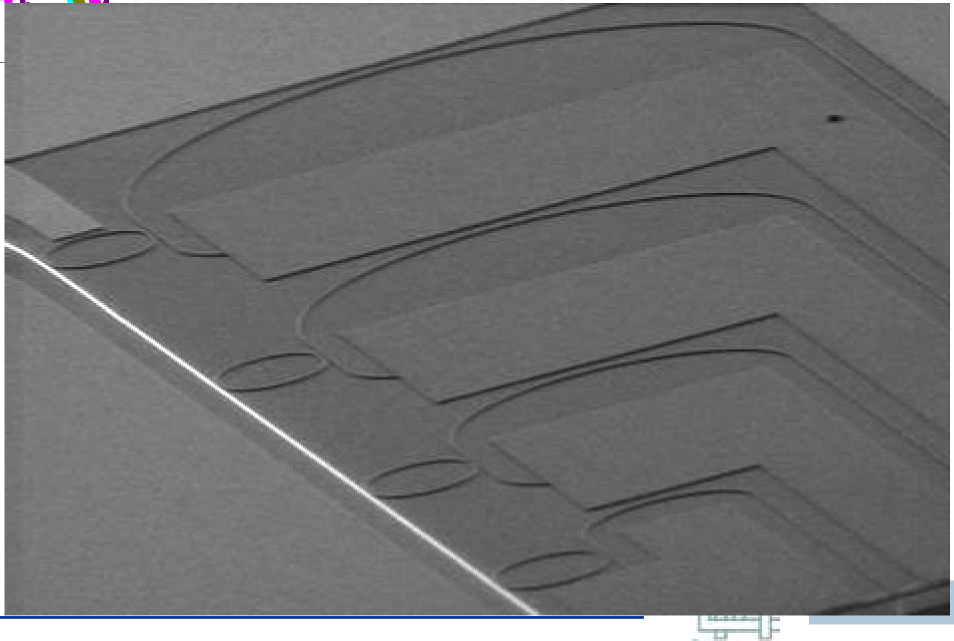


Optical Ring Resonators



Ring resonator demux

- 4 rings in series
- Linearly increasing radius
- λ_c does not increase linearly as expected !!
- Fabrication problem: mask discretisation

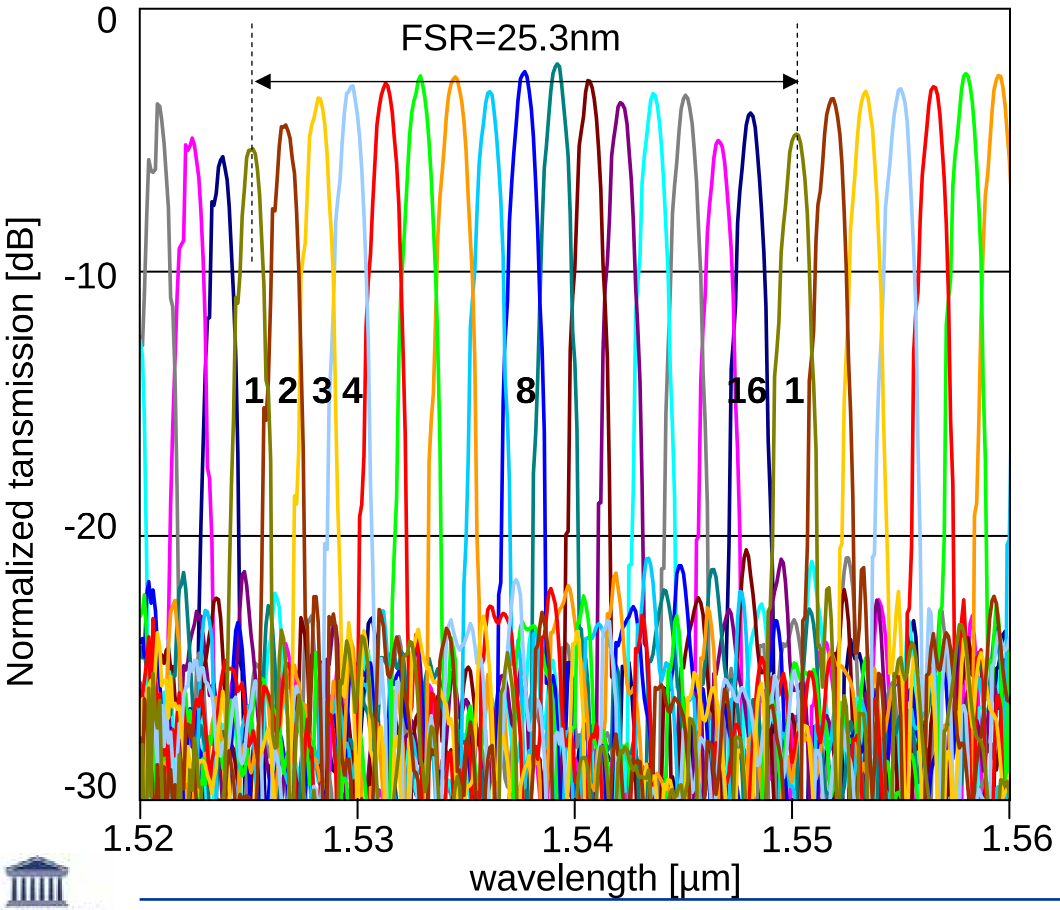


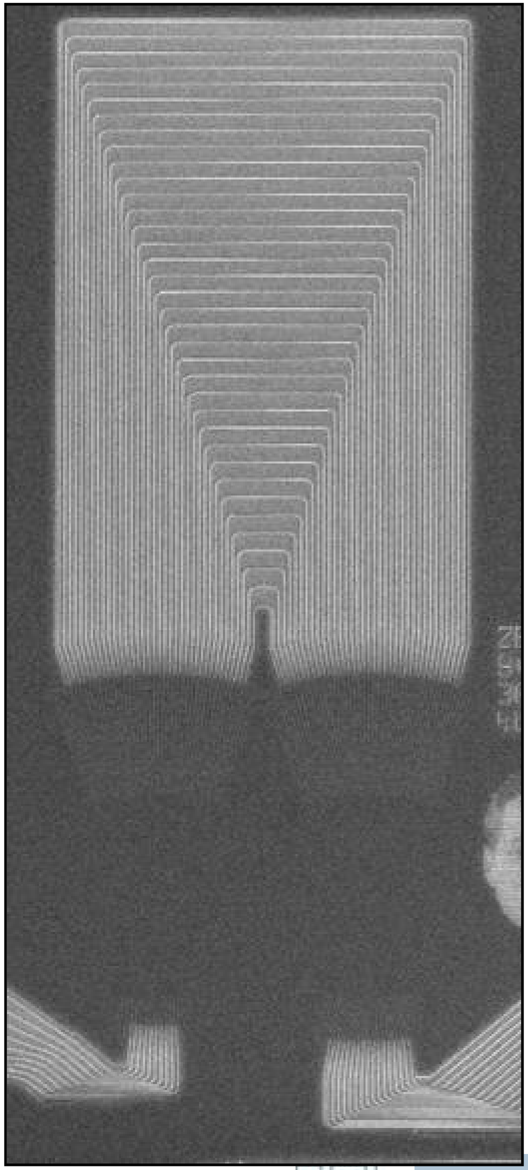
Arrayed Waveguide Grating

16-channel AWG, 200GHz

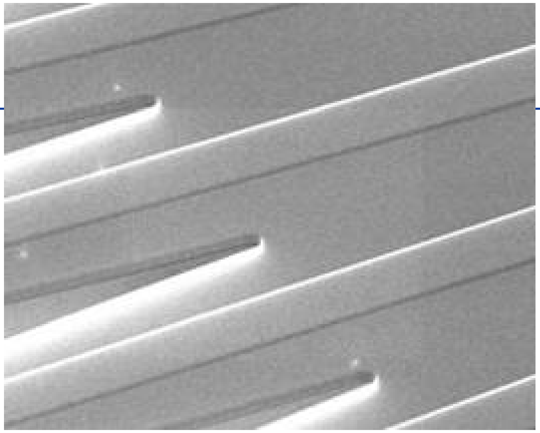
200µm x 500µm area

- **-3dB insertion loss**
- **-15dB to -20dB crosstalk**



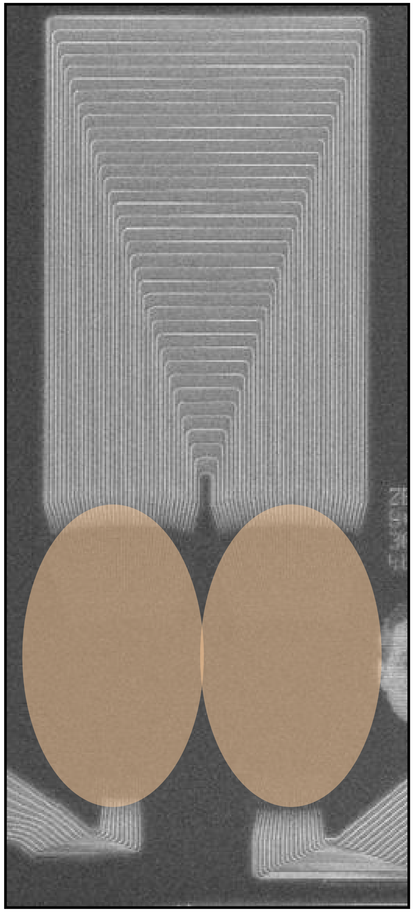


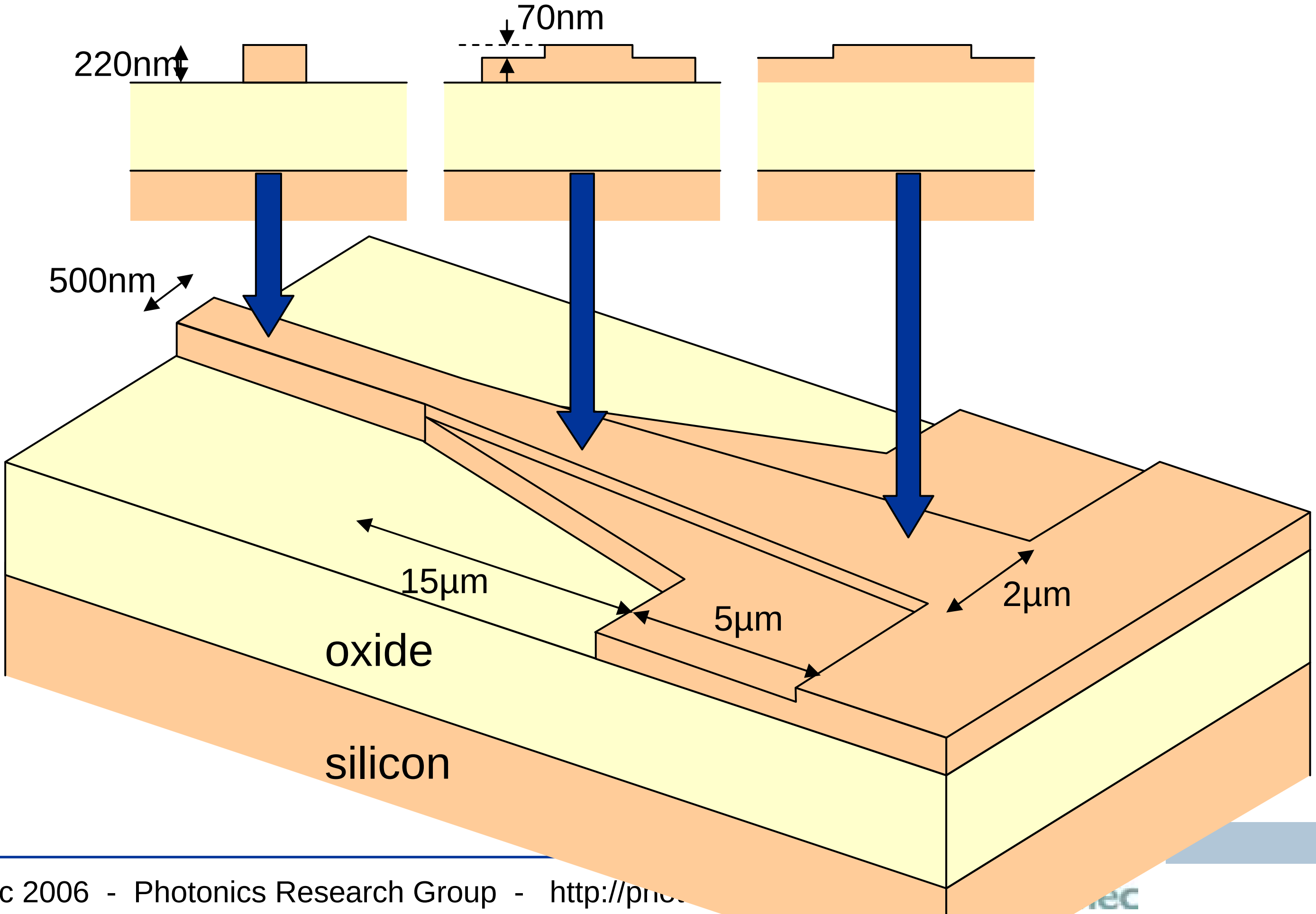
Deep and shallow etch



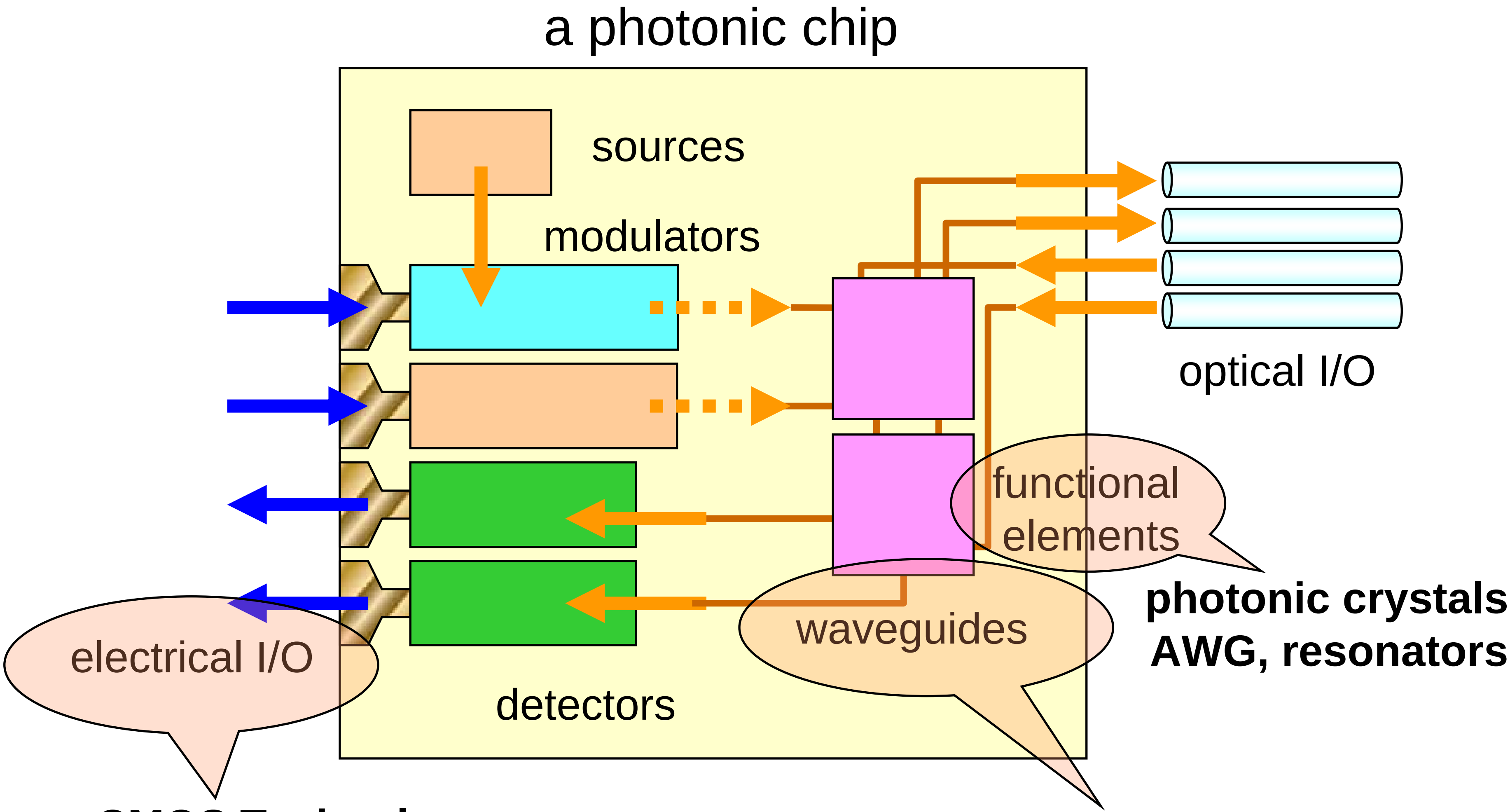
Star coupler:

- shallow etch for less contrast





What can WE do in Silicon?

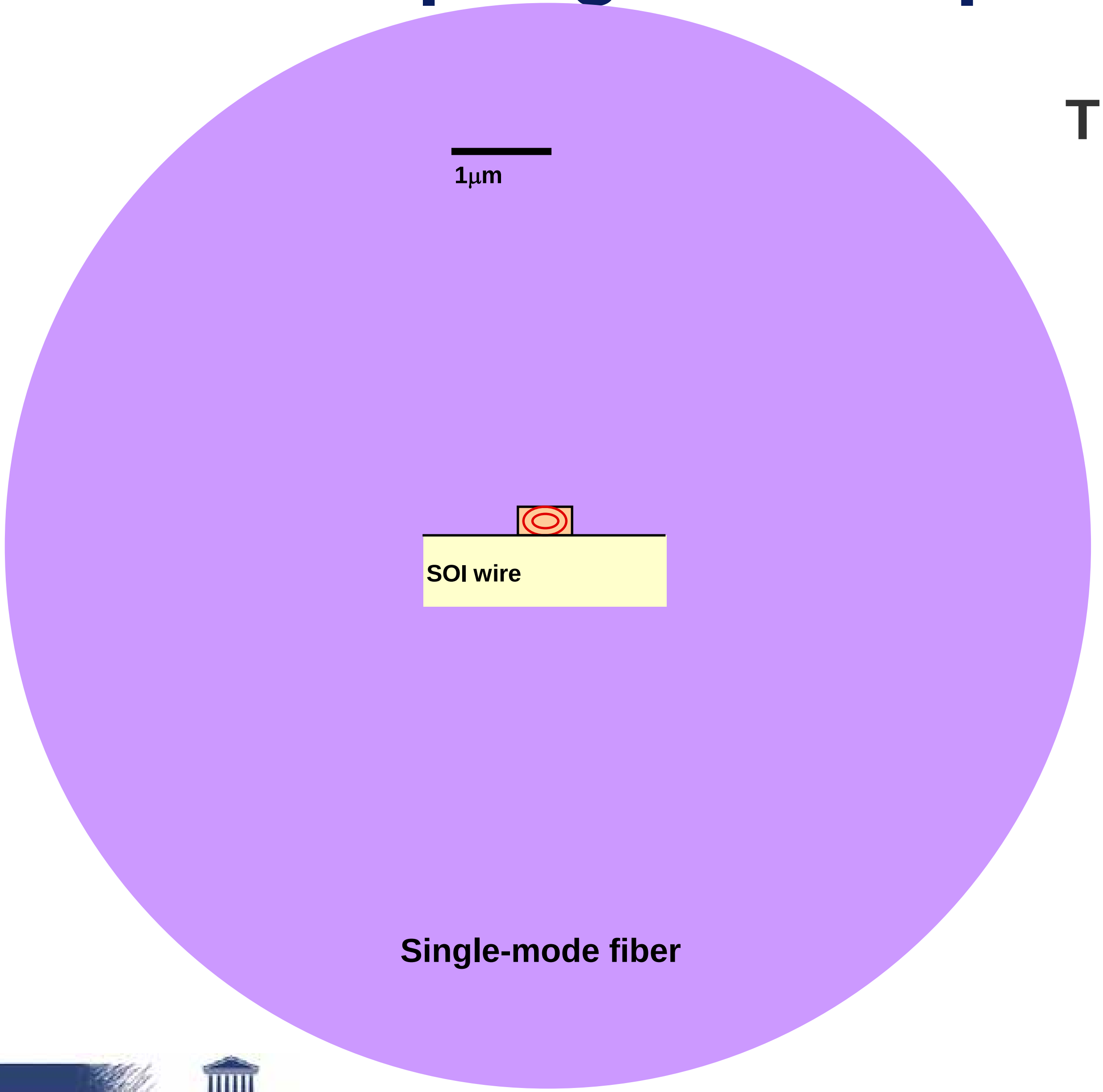


photonic crystals AWG, resonators

CMOS Technology

photonic wires

Coupling to nanophotonics



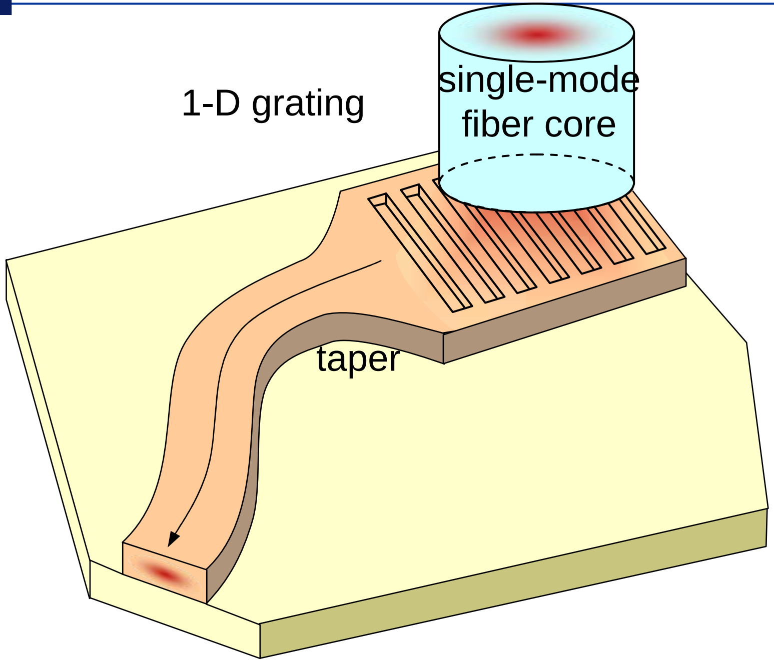
The problem

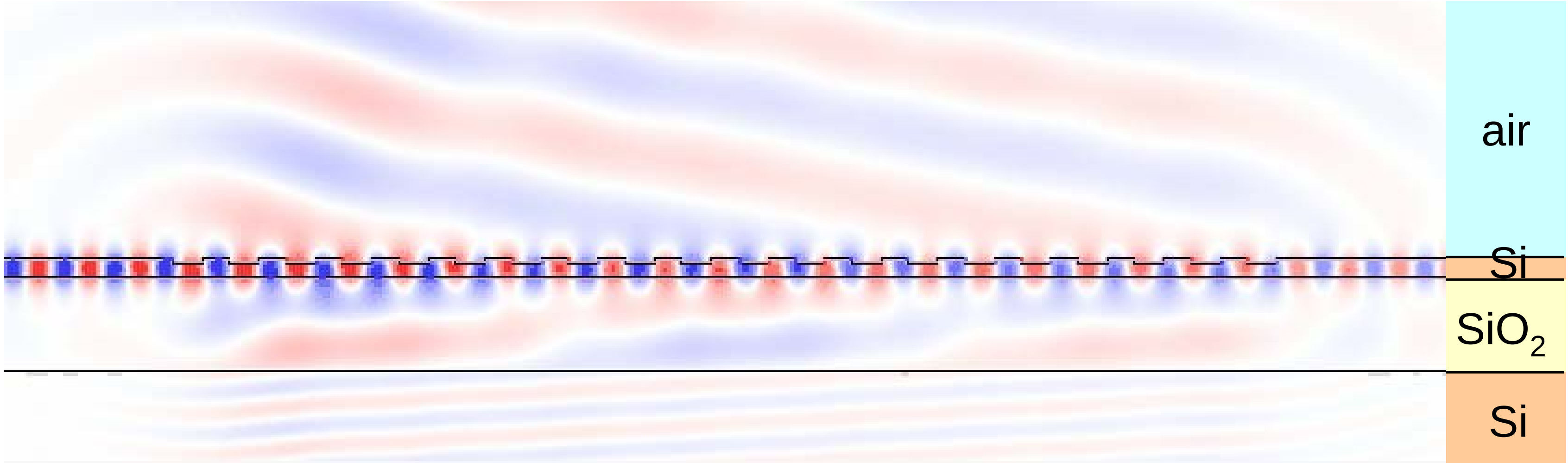
- efficient coupling between a submicrometre waveguide and a fiber
- spot-size converter needed :
  - in plane (horizontal)
  - out-of-plane (vertical) : more difficult
- the polarization problem

Vertical Fibre Coupler

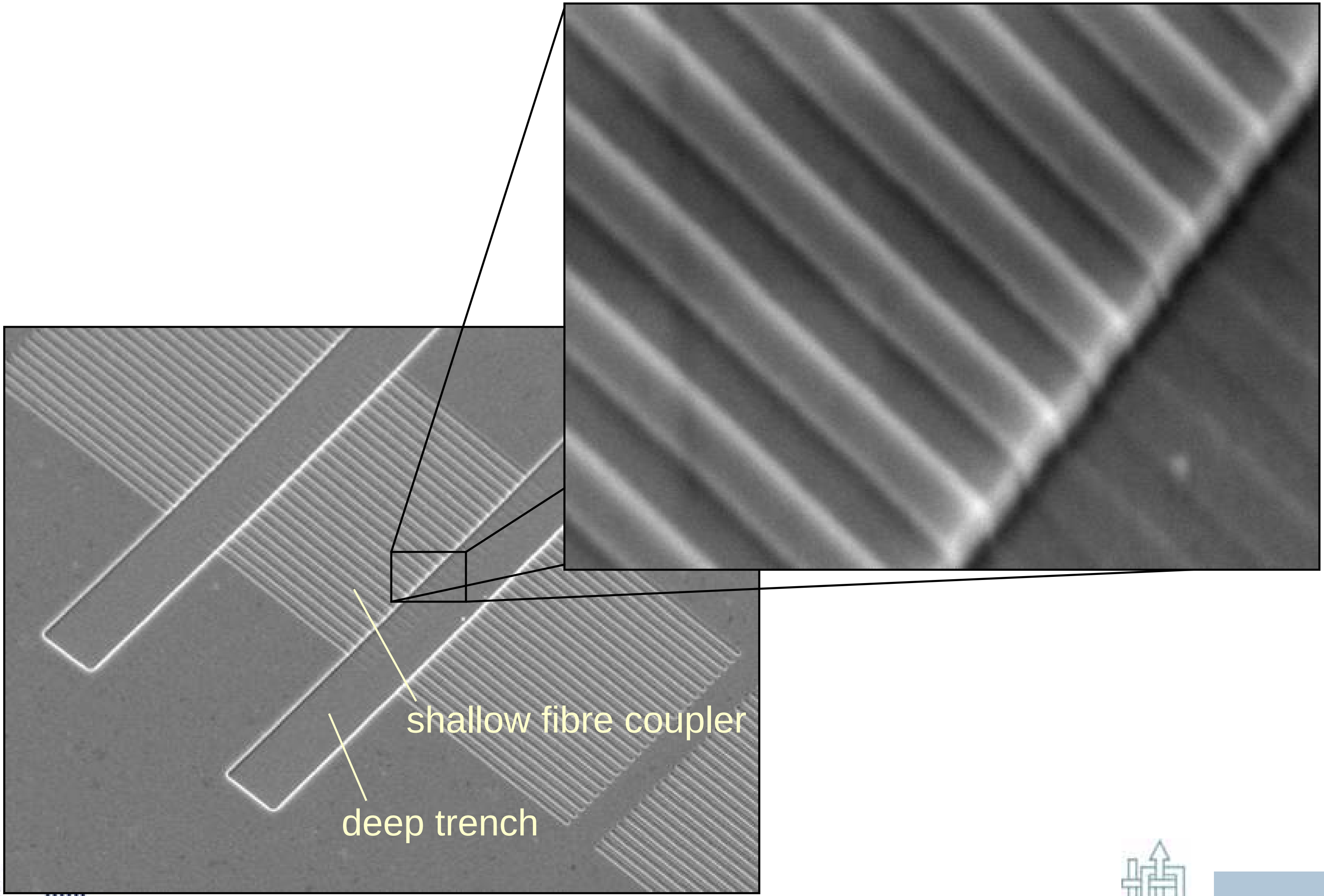
1-D grating

- **Butt-coupled**
- **Period ~ 600nm**
- **20 periods**
- **Etch depth = 45nm**
- **Optimized design: 31% coupling**

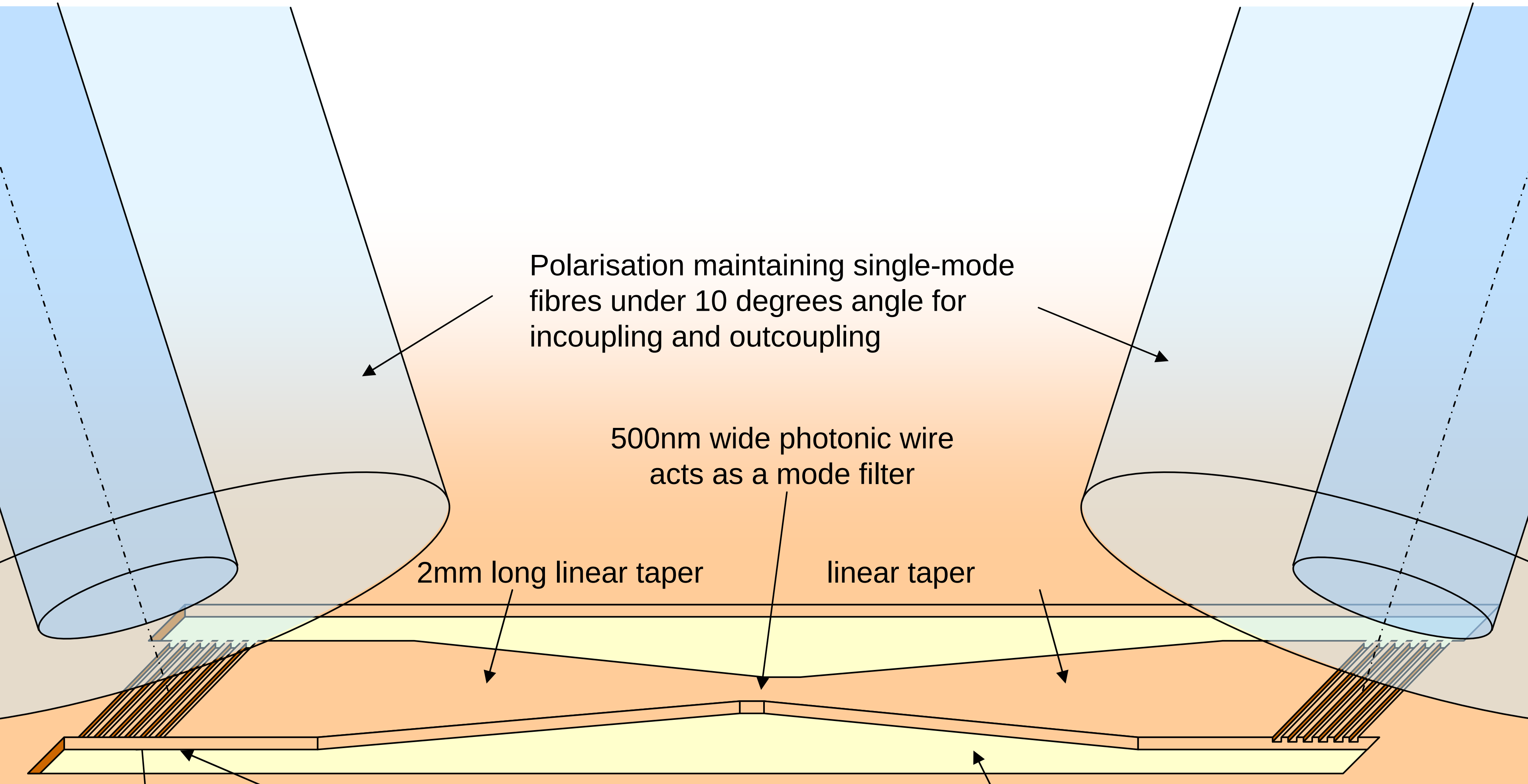




Fiber coupler grating



I/O with Fibre Coupler gratings



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

500nm wide photonic wire acts as a mode filter

2mm long linear taper

linear taper

10μm ridge waveguide to match width of fibre mode

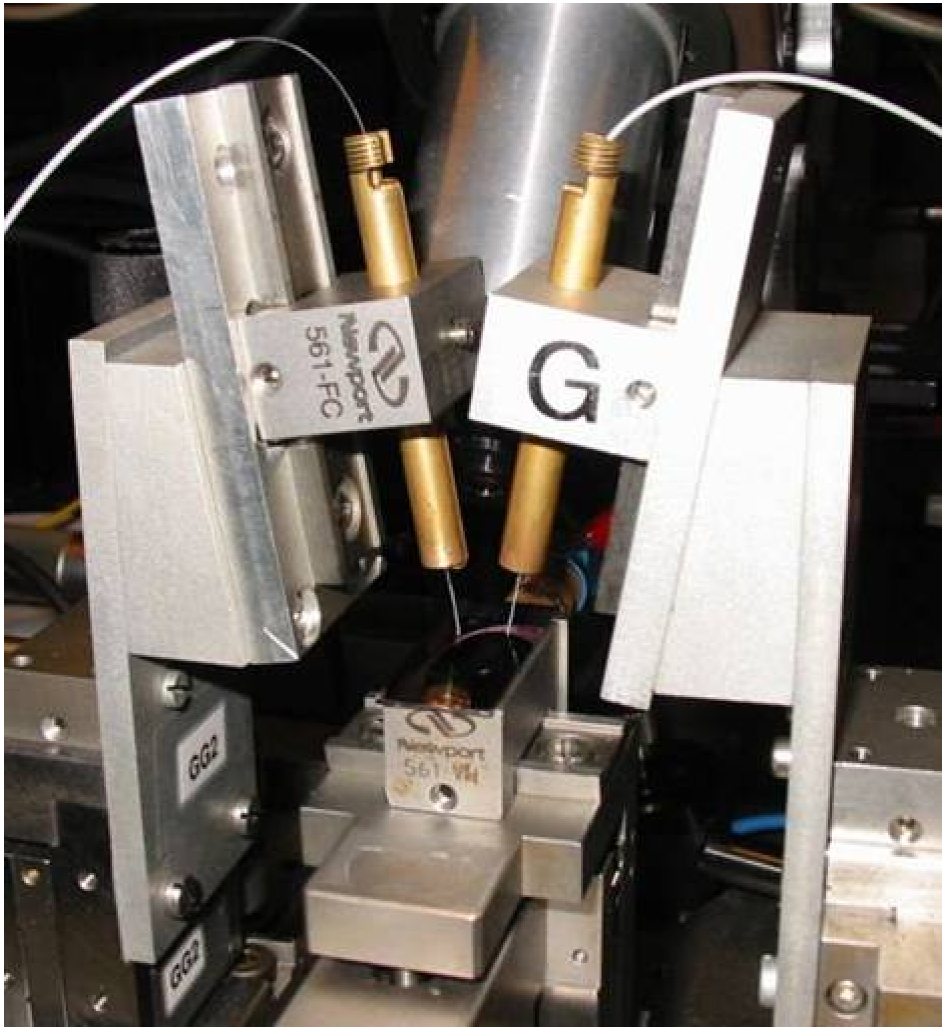
Oxide bottom cladding

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

Fiber coupler measurements

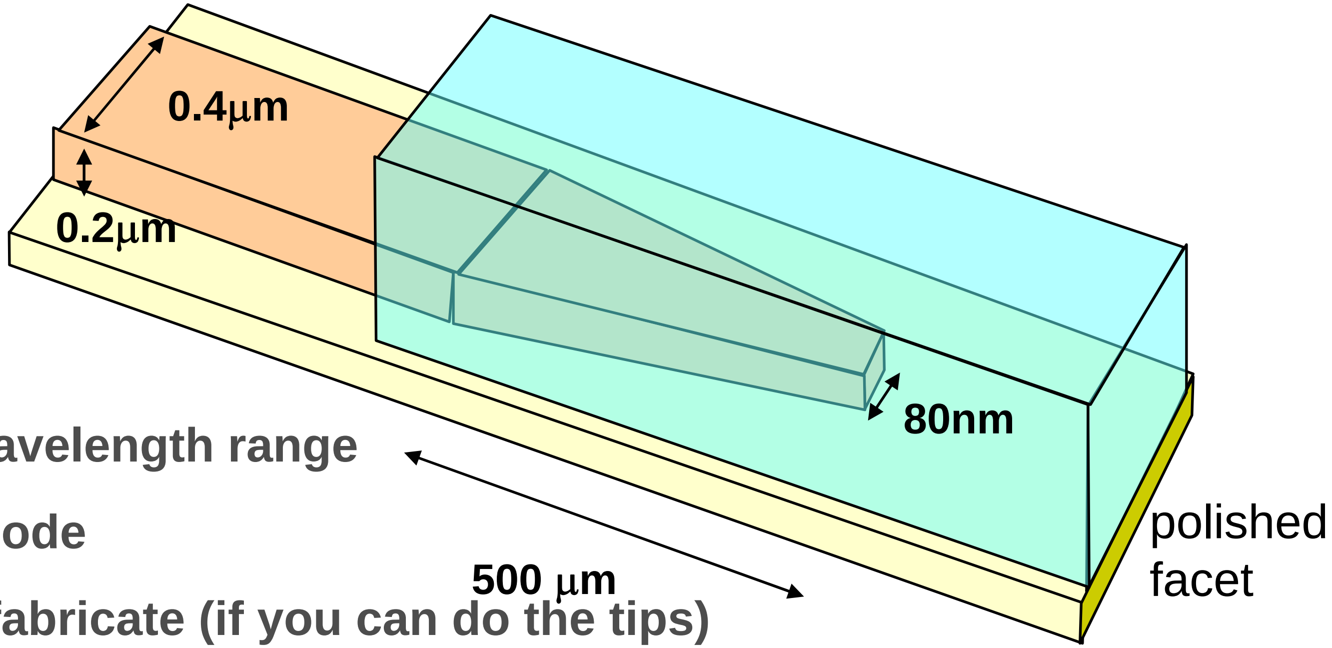
Measurement setup

- no facets needed
- wafer-scale testing becomes possible



Alternative: Polymer Taper

- Inverse taper



- Broad wavelength range
- Single mode
- Easy to fabricate (if you can do the tips)
- Low facet reflections

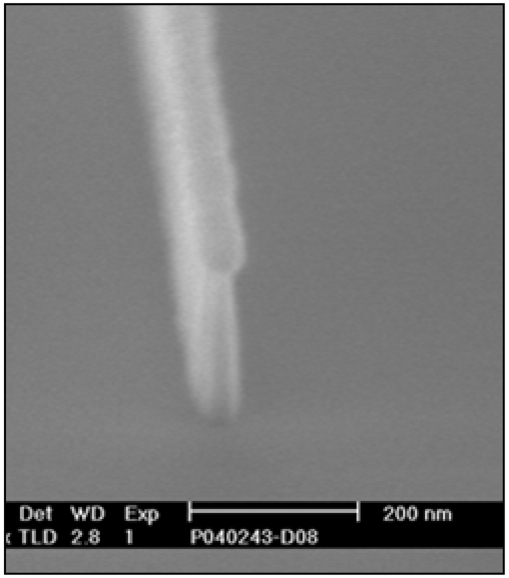
NTT Shoji et al. EL 38, p.1669 (2002)
IBM McNab et al. OpEx 11(22), P. 2927 (2003)
Roelkens et al. PTL 17(12), p. 2613 (2005)

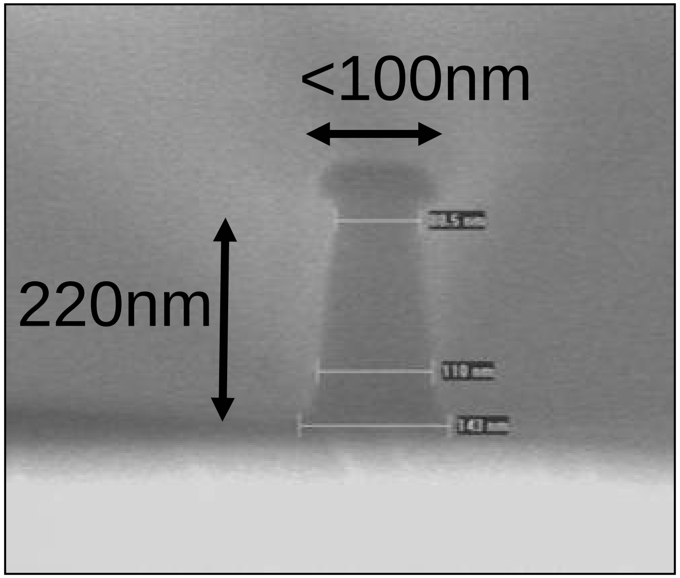
Narrow tip for polymer tapers

Tip fabrication

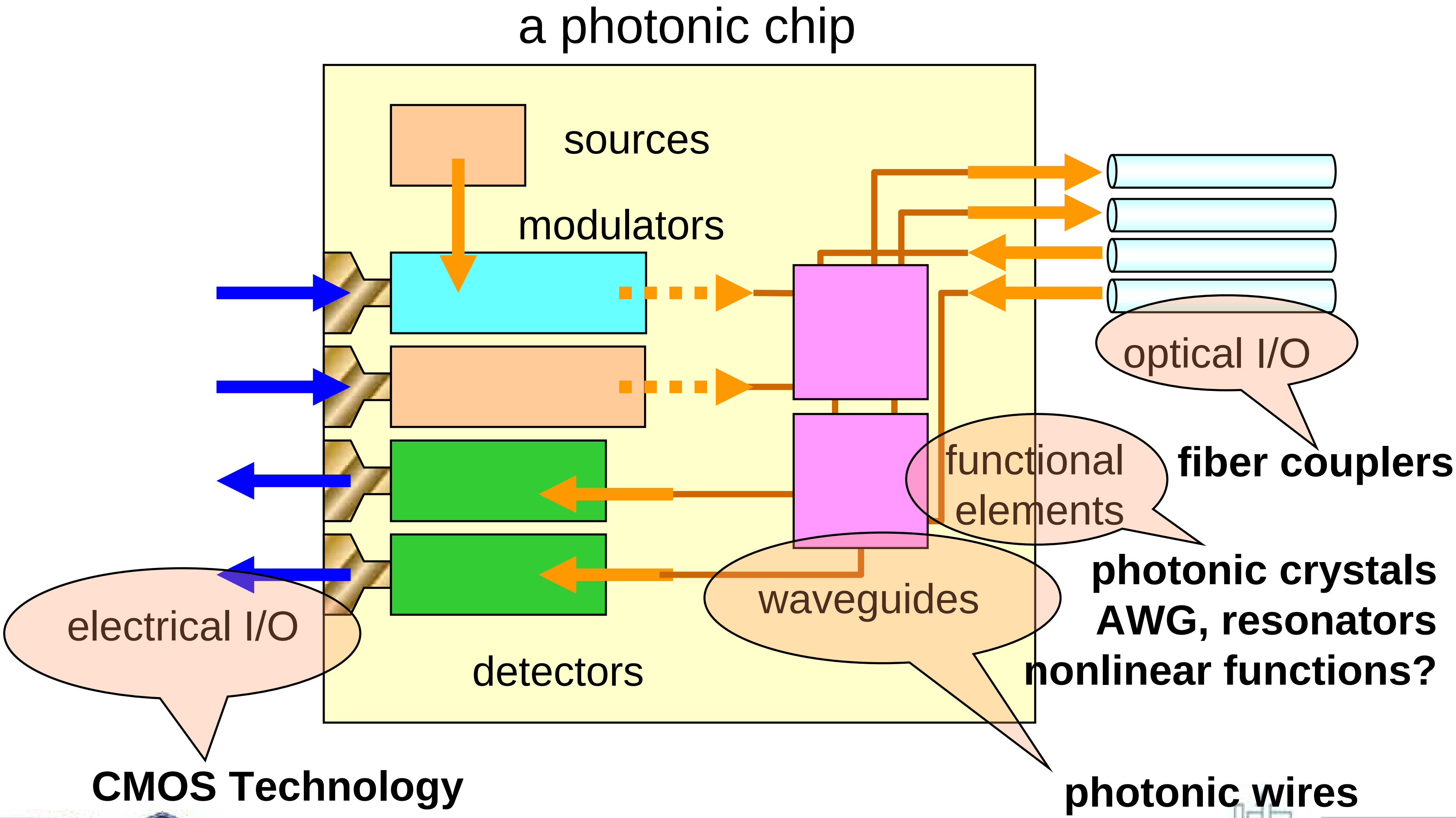
- 248nm DUV: 140nm
- resist trimming: 105nm
- hardmask trimming: 80nm

But: unwanted trimming of other structures





What can WE do IN Silicon?



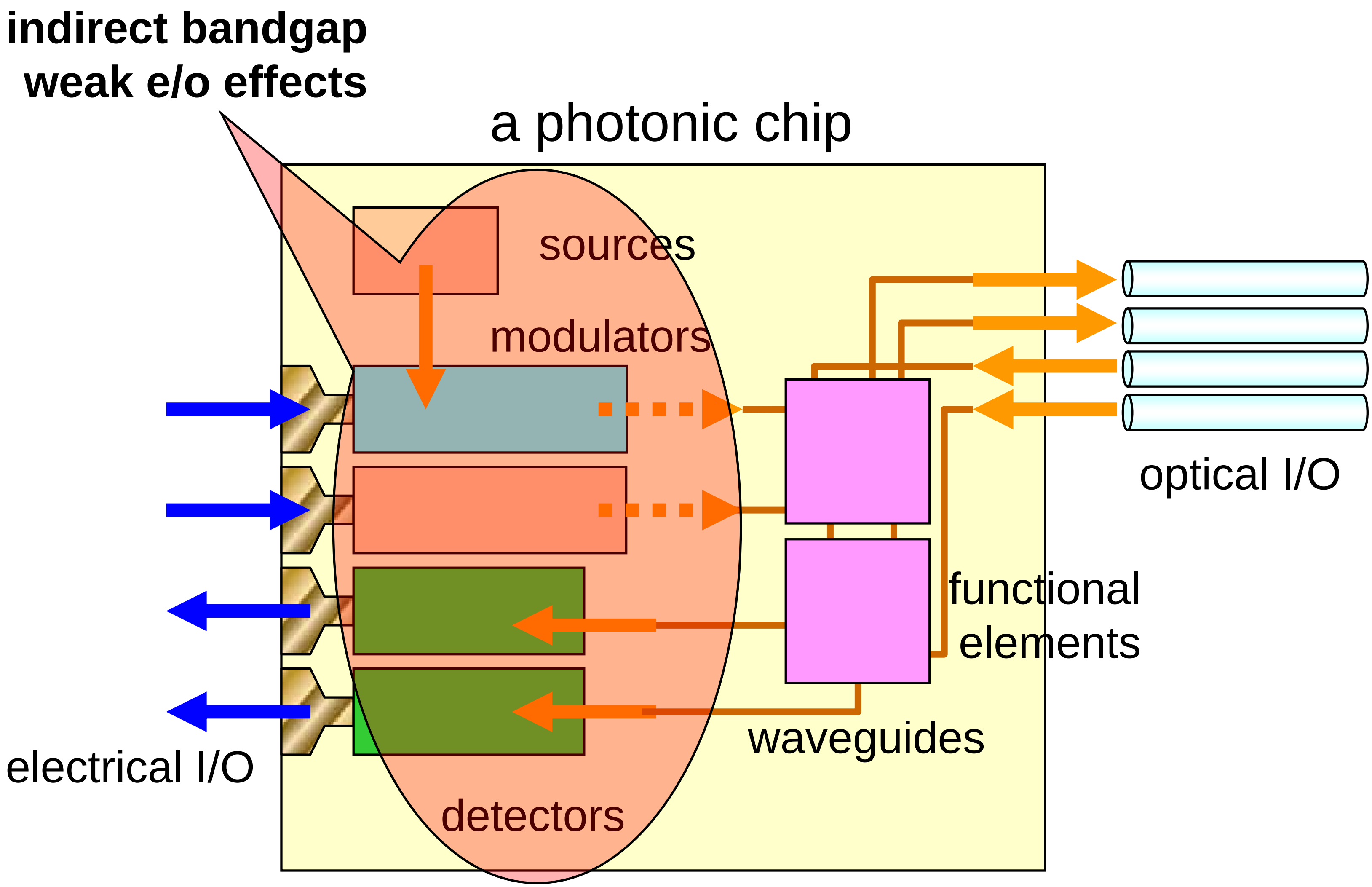
fiber couplers

photonic crystals
AWG, resonators
nonlinear functions?

CMOS Technology

photonic wires

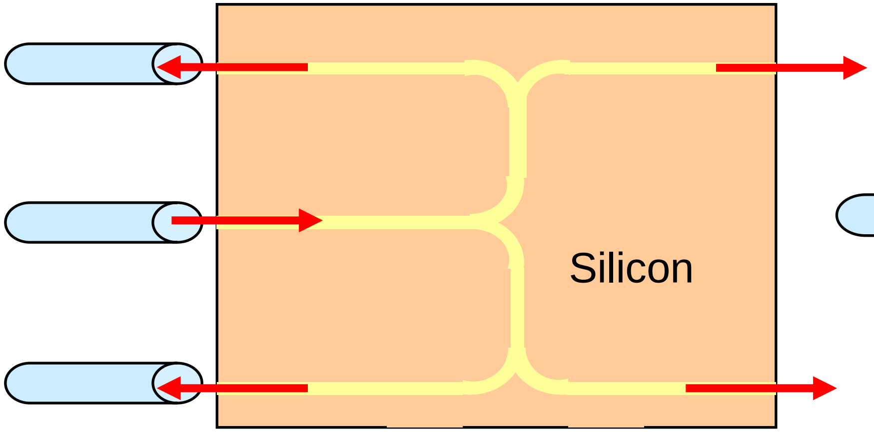
What is really difficult in Silicon?



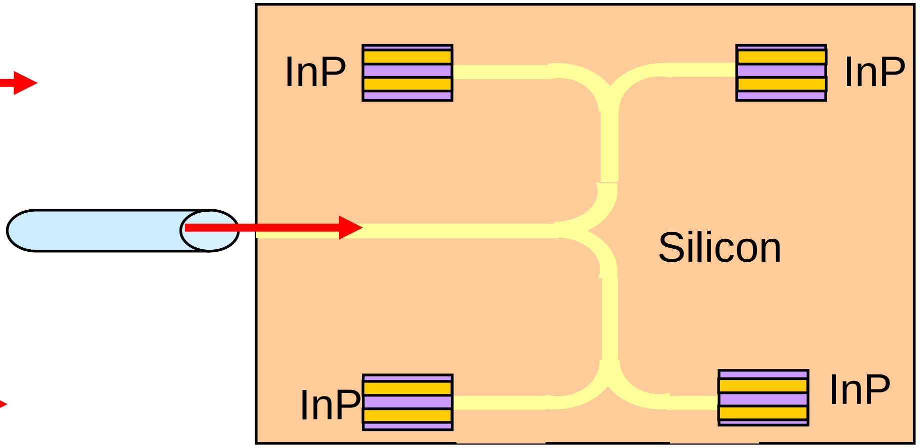
Heterogeneous integration

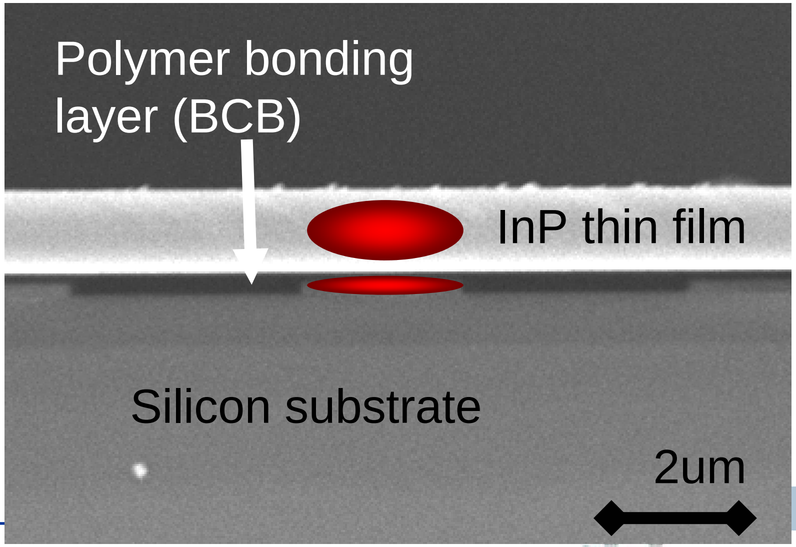
Silicon waveguide structure → *Heterogeneous circuit*

Passive only

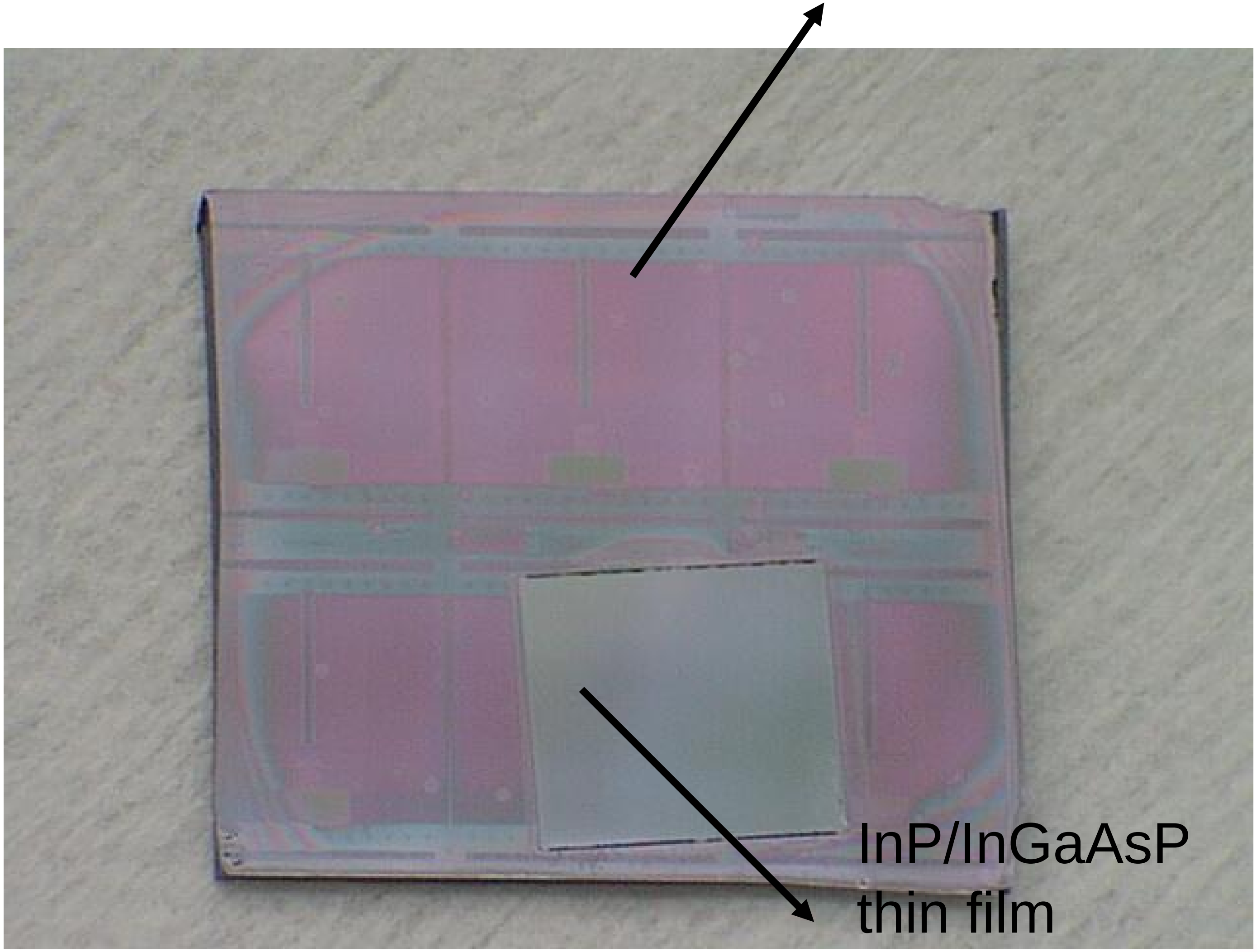


Active + passive





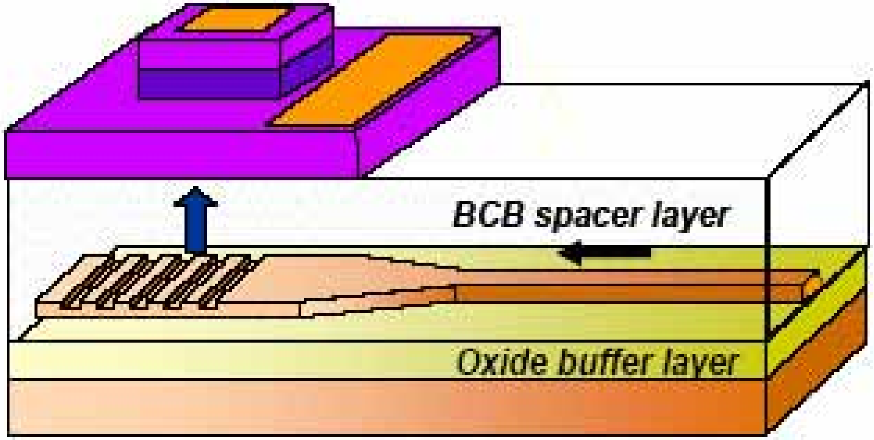
Die to wafer bonding with BCB

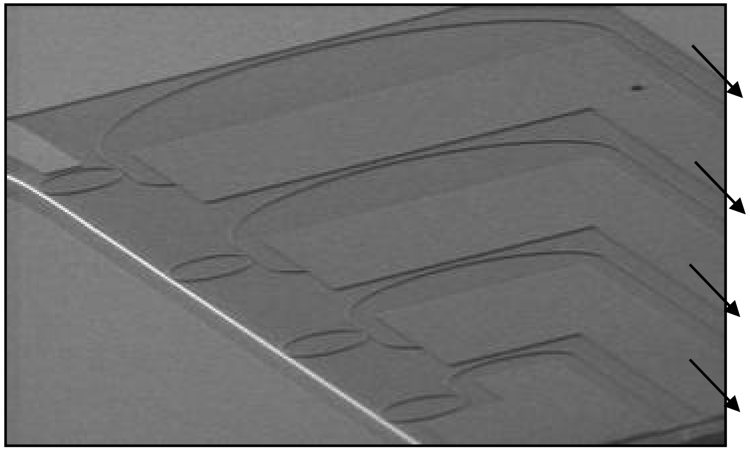


Processed SOI substrate

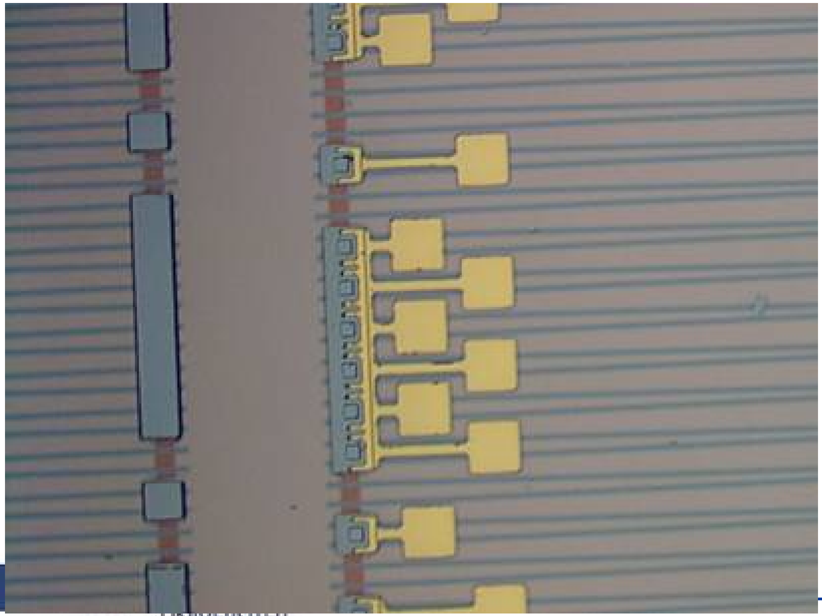
InP/InGaAsP thin film

InGaAs Detectors on SOI

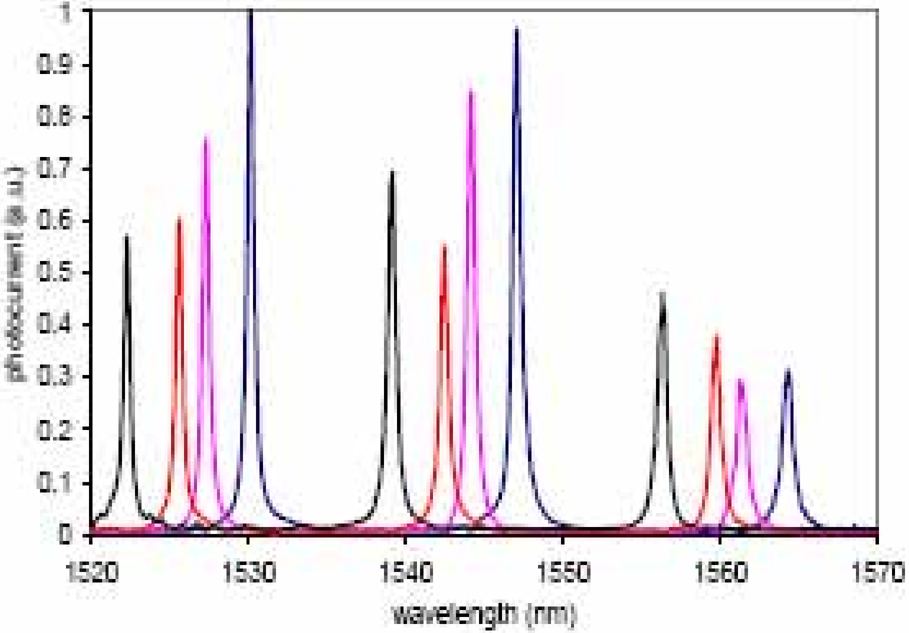




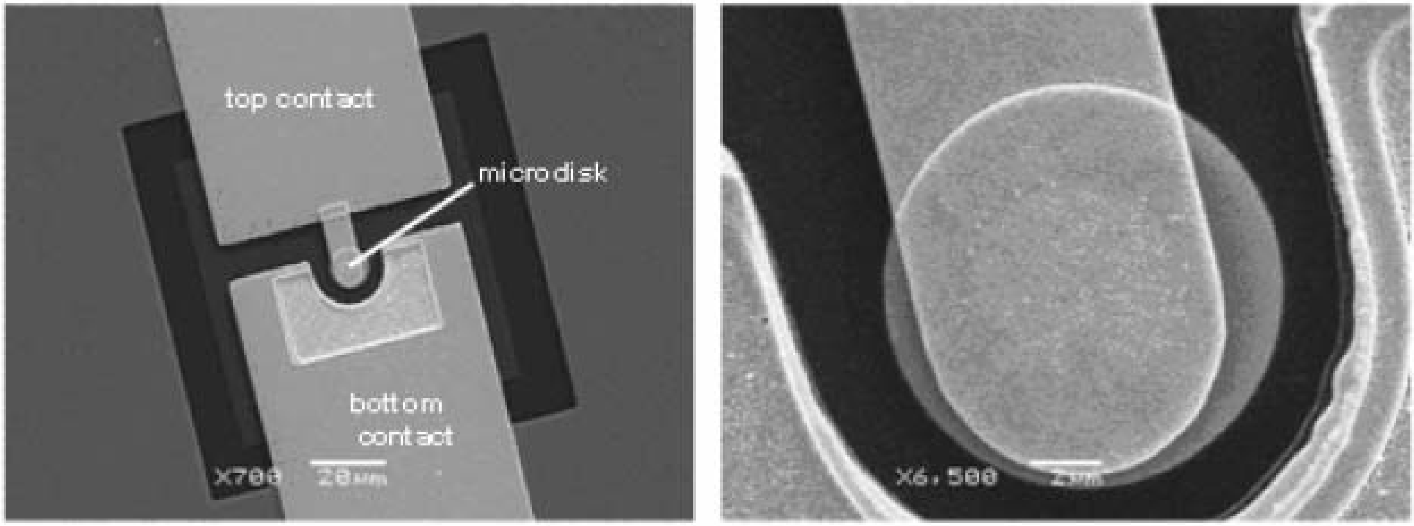
To detectors



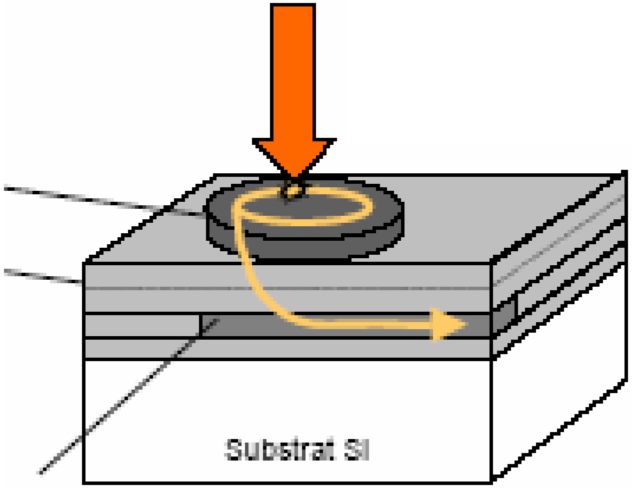
Measured response of 4 detectors

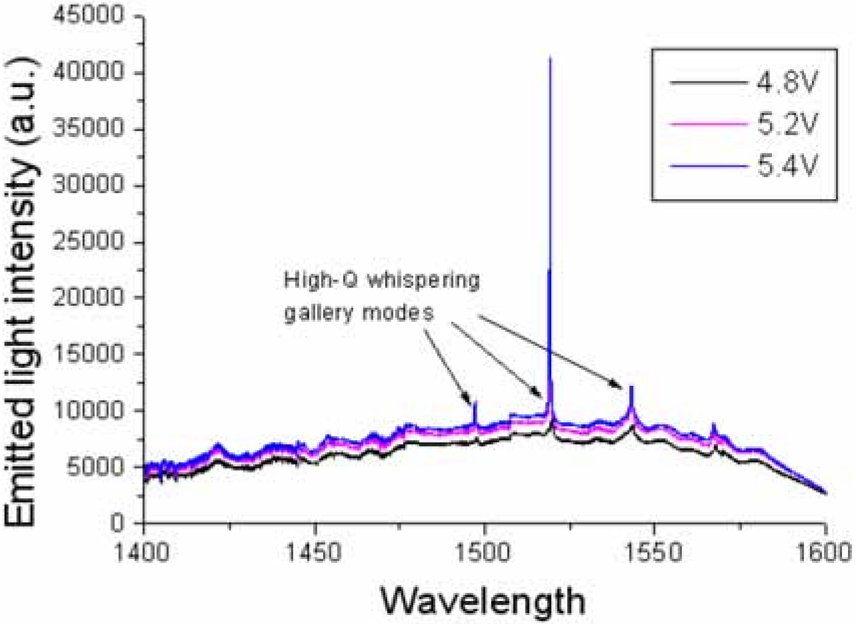


Electrically pumped InP µdisk laser

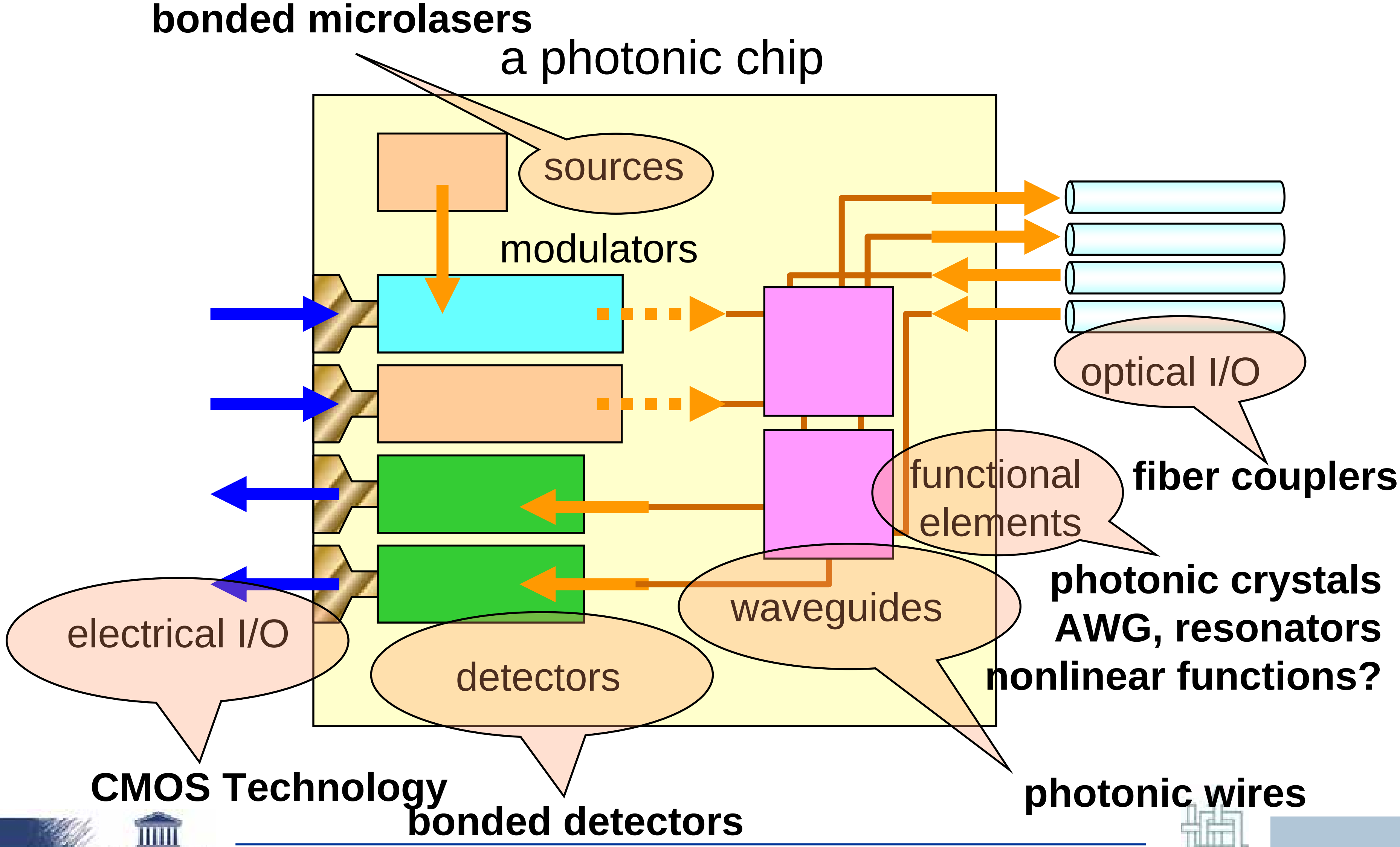


PICMOS





What can we do IN and ON Silicon?



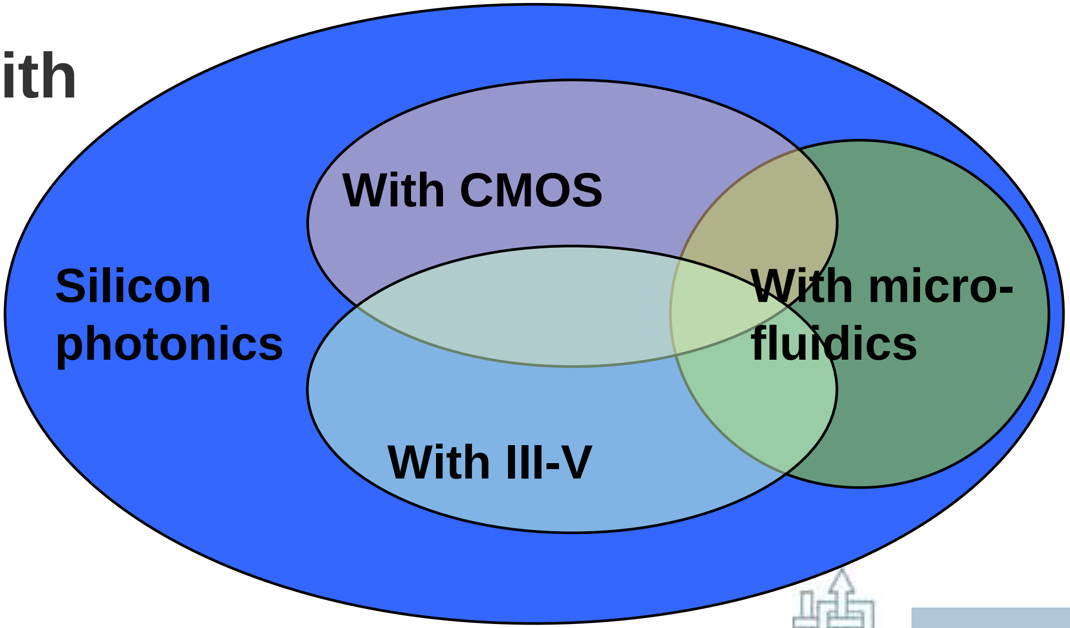
Applications

What can/could we do with SOI nanophotonics?

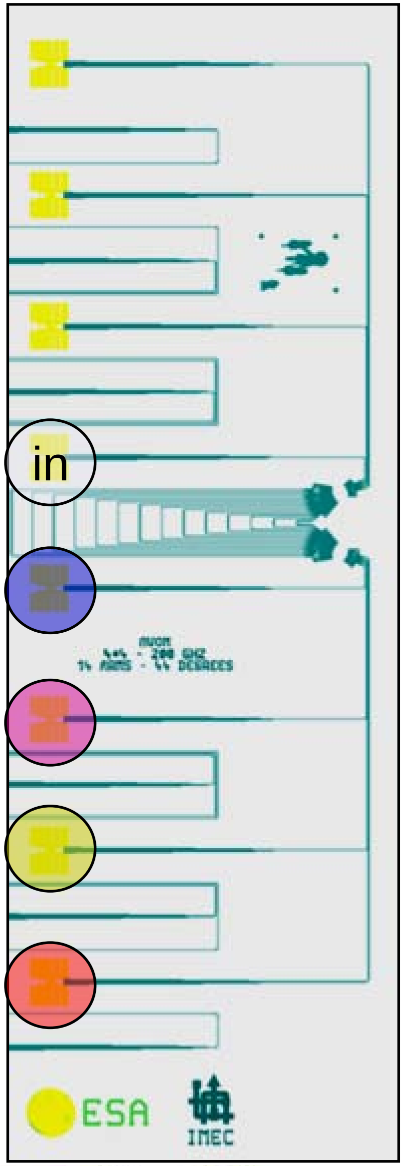
- Wavelength selective elements for telecom
- Inter-chip and intra-chip communication
- Strain and pressure sensors
- Optical bio-sensors
- Lab-on-a-chip

by combining SOI with

- III-V (InP, GaAs)
- overlay claddings
- MEMS
- µ-fluidics
- ...



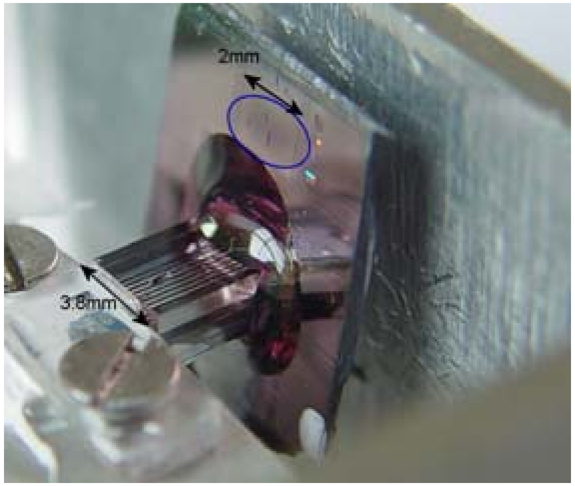
Optical interconnect in space

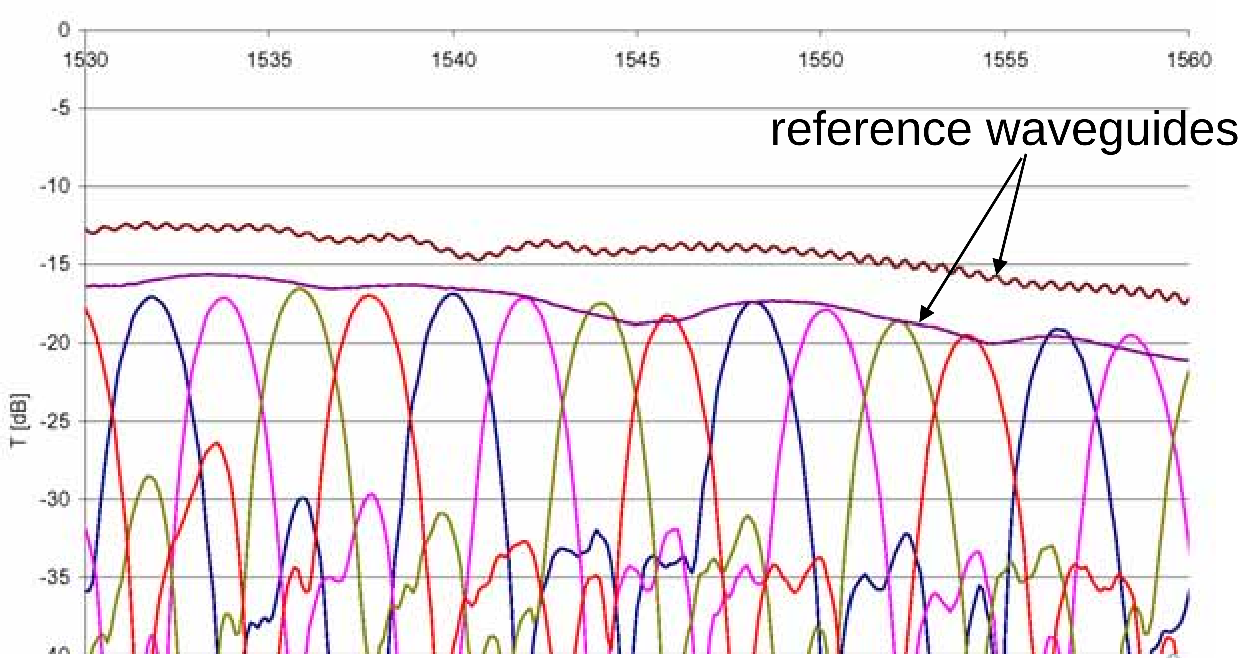


4 x 4 wavelength router:

Interconnect 4 subsystems

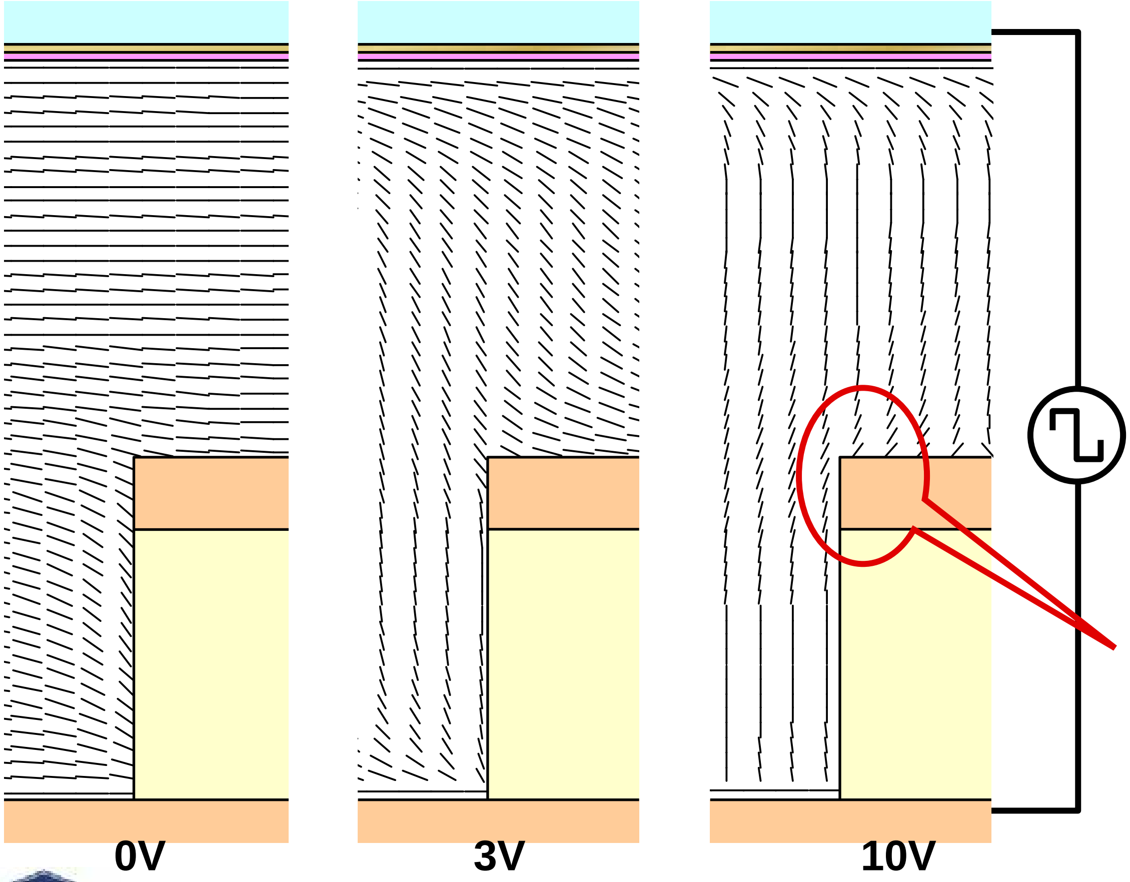
- **Four inputs and four outputs in standard array connector**
- **20dB power budget**
- **10-15 dB crosstalk**





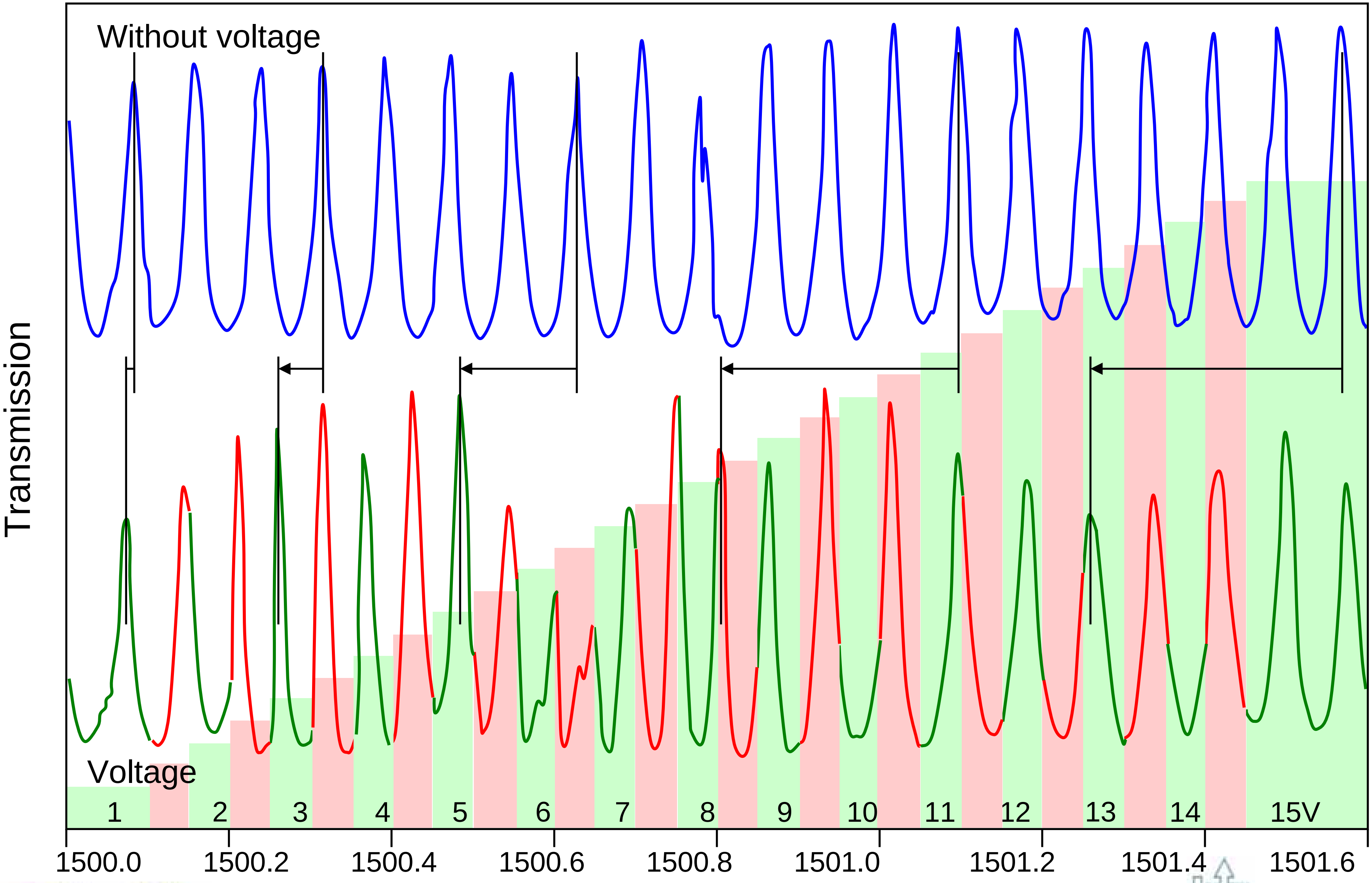
Liquid Crystal cladding

- Liquid crystal: anistropic material
- Surface forces: LC is oriented parallel to the surface
- Apply voltage: LC molecules rotate: Change in refractive index



Unpredictable effects:
- unknown geometry
- bent field-lines

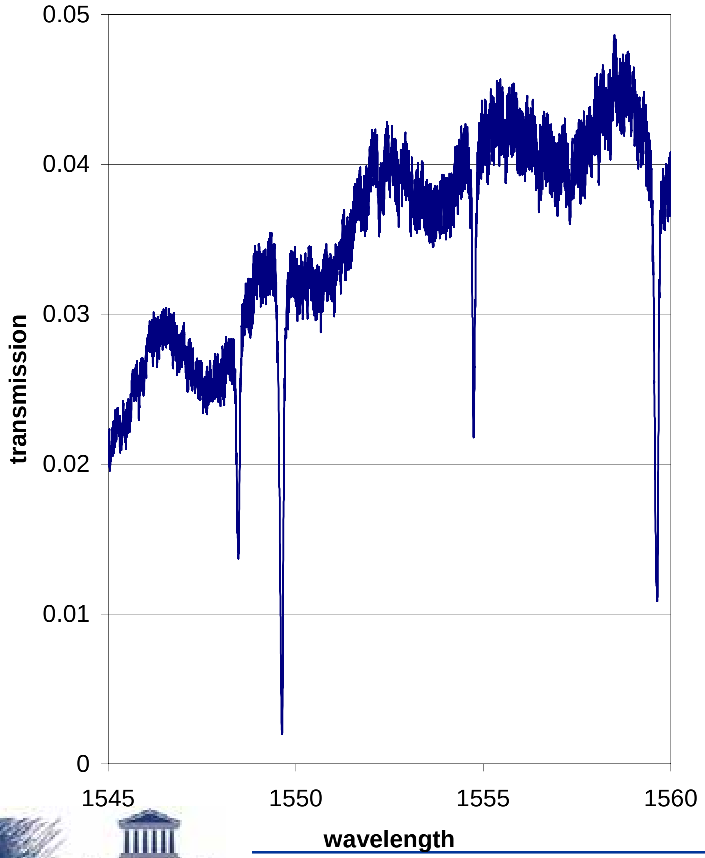
Resonances of cavity

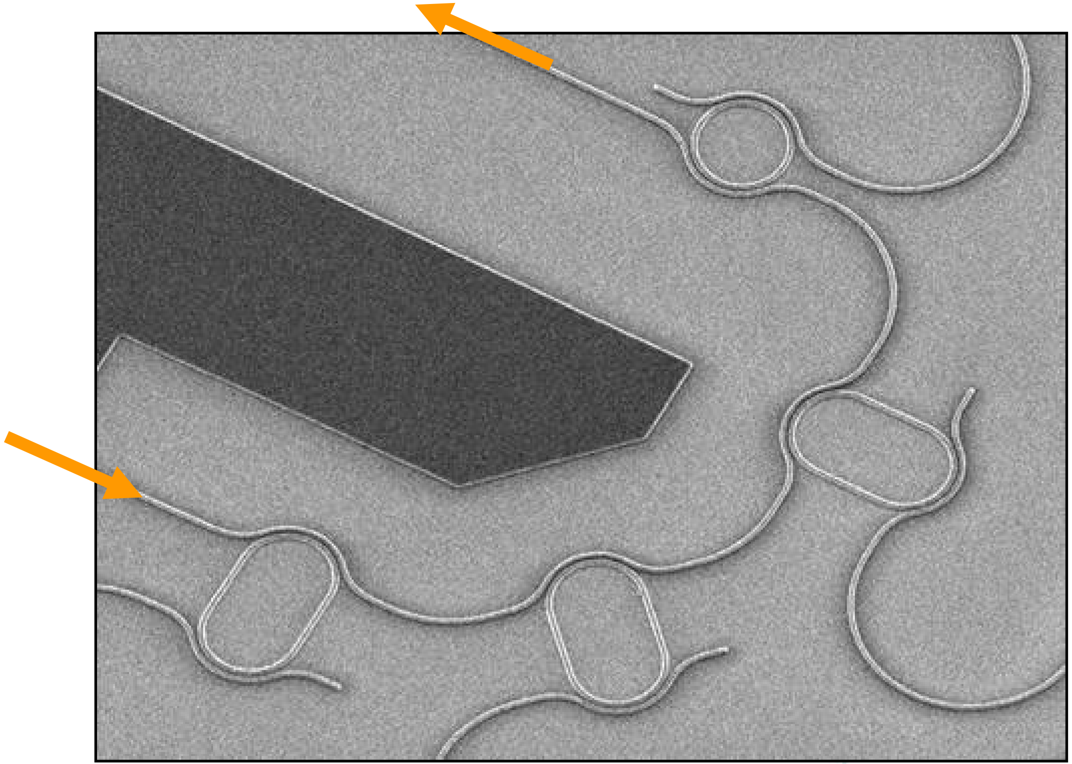


Strain Sensors

2-D Strain sensor with 4 ring resonators

- X and Y strain
- shear
- calibration (temperature, ...)

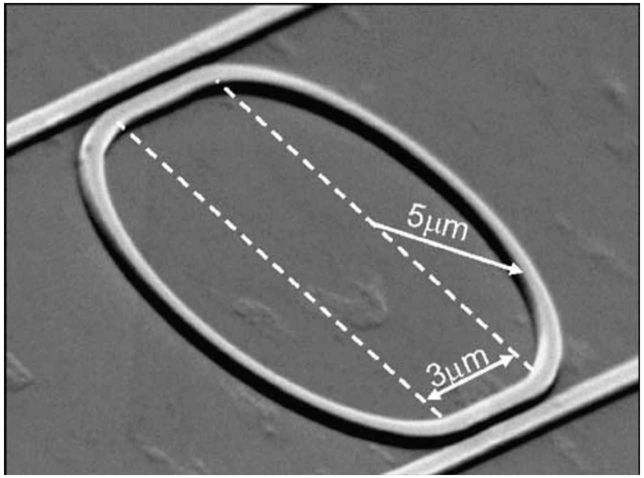


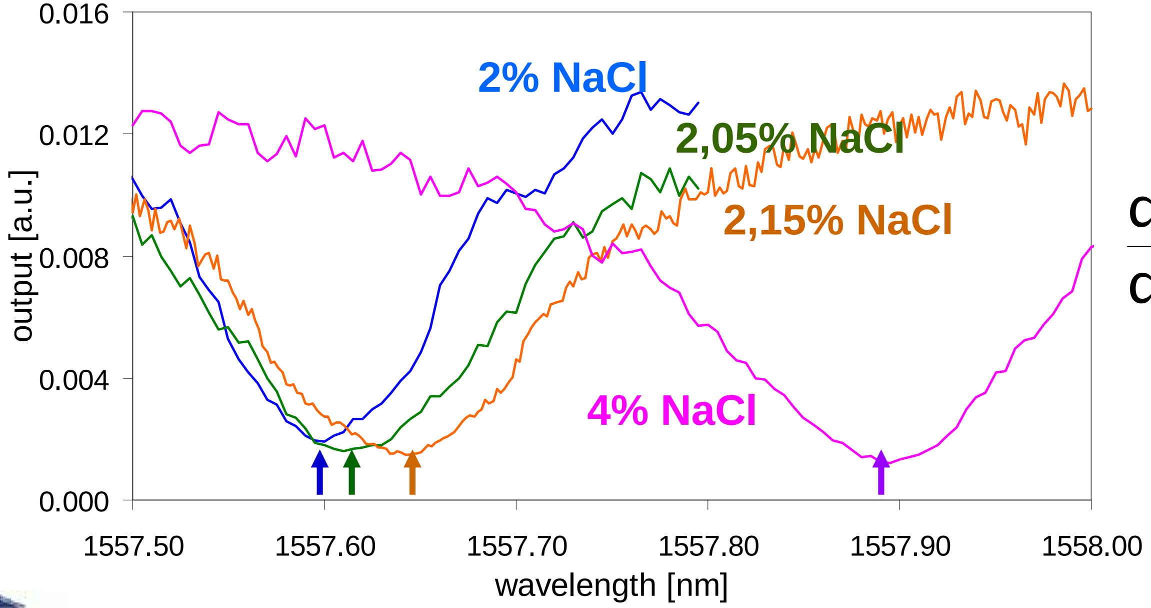


SOI microring sensor

Measure salt concentration

- Fluid overcladding
- Refr. index ~ Salt concentration
- Response of ring ~ refr. index
- Q = 20000 → minimum $\Delta n \sim 5.10^{-5}$





$$\frac{d\lambda}{dn} = 86{,}6\text{nm}/\text{RIU}$$

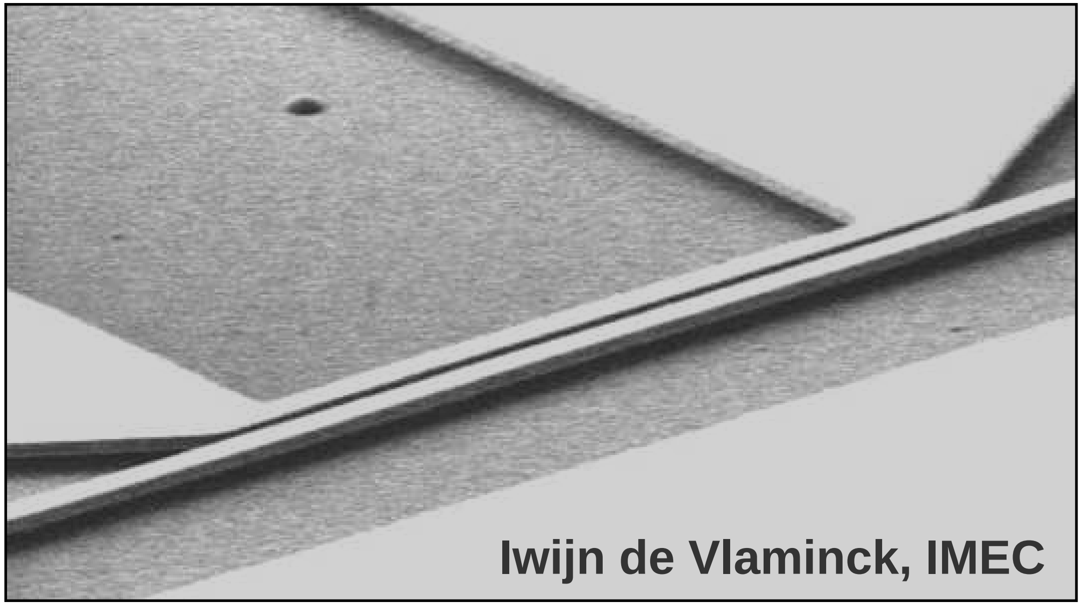
SOI NEMS Vibration Sensor

SOI directional coupler

- 2 waveguides close together: light leaks
- coupling efficiency ~ waveguide spacing

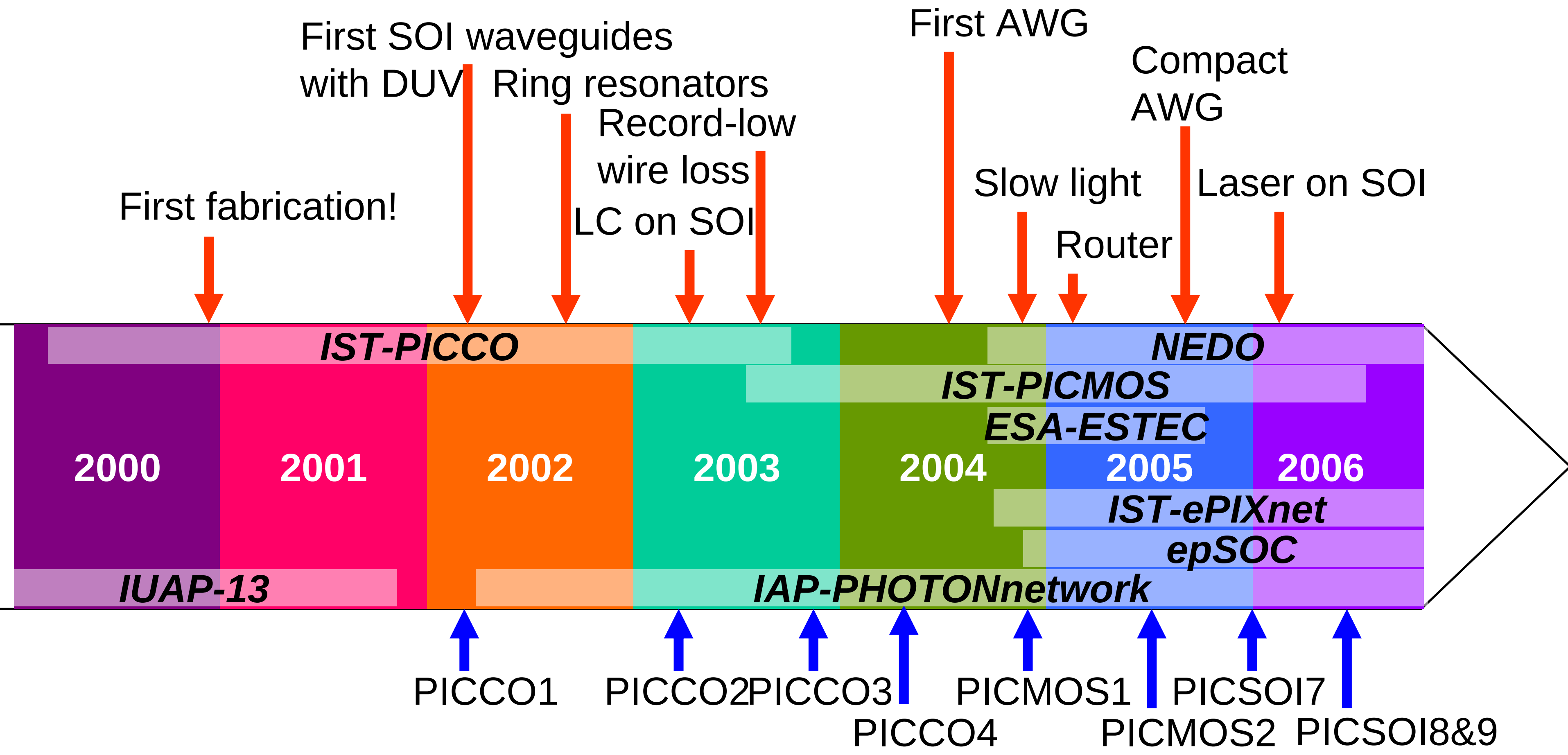
Freely Suspended directional coupler

- Oxide removal
- Vibrations change spacing



Iwijn de Vlaminck, IMEC

Our Silicon Photonics Timeline



First fabrication!

First SOI waveguides with DUV

Ring resonators

LC on SOI

Record-low wire loss

First AWG

Slow light

Router

Compact AWG

Laser on SOI

2000

2001

2002

2003

2004

2005

2006

IST-PICCO

NEDO

IST-PICMOS

ESA-ESTEC

IST-ePIXnet

epSOC

IUAP-13

IAP-PHOTONnetwork

PICCO1

PICCO2

PICCO3

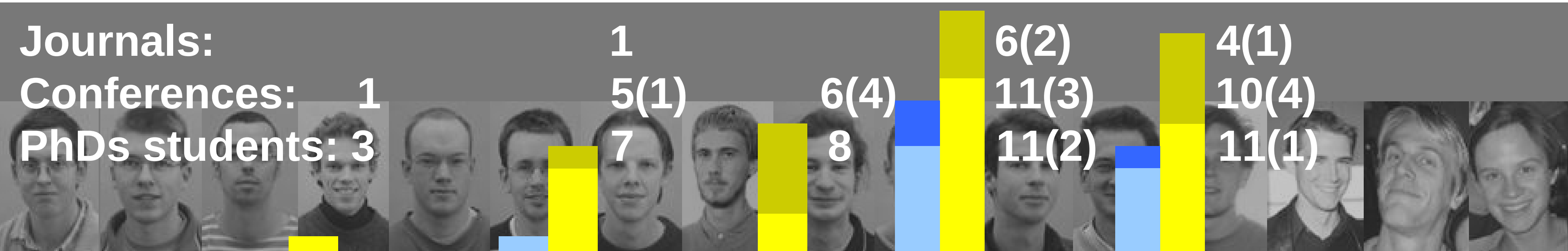
PICCO4

PICMOS1

PICMOS2

PICSOI7

PICSOI8&9

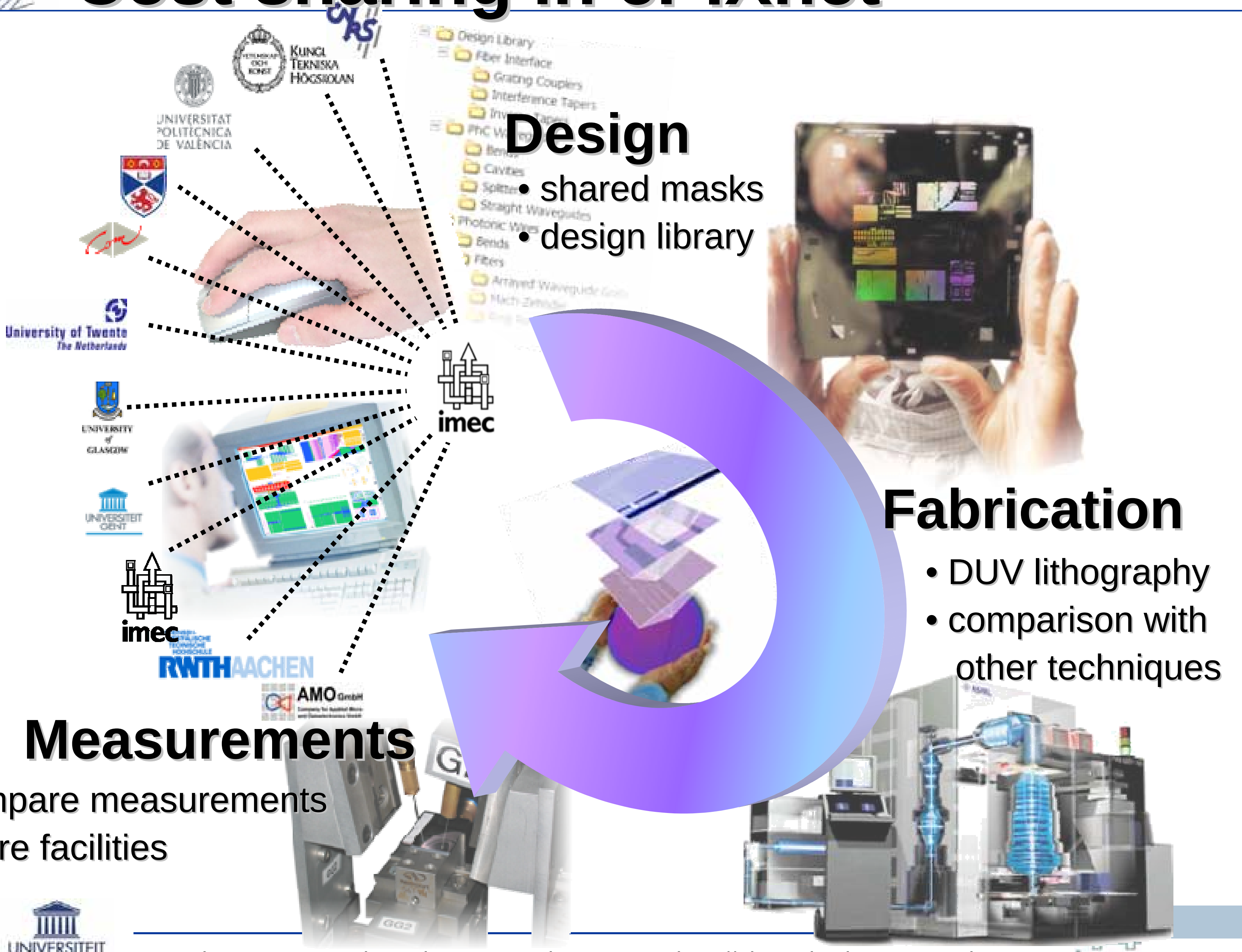


Journals: 1 6(2) 4(1)

Conferences: 1 5(1) 6(4) 11(3) 10(4)

PhDs students: 3 7 8 11(2) 11(1)

Cost sharing in ePIXnet



Design

- shared masks
- design library

Fabrication

- DUV lithography
- comparison with other techniques

Measurements

- compare measurements
- share facilities

Silicon photonics platform

Next step: join forces in Silicon Photonics

- IMEC
- LETI

Fabrication for SOI nanophotonics

- Only standard processes (e.g. waveguides)
- Standard modules (e.g. fiber couplers)

Support the SOI nanophotonics community

- design libraries and software
- organise exchanges (e.g. for measurements)

ePIXnet

Overview of this presentation

Background on Photonics

- What’s the use?
- How does a waveguide work?
- Photonic Crystals
- SOI Nanophotonics

UGent - IMEC achievements

- Wha
- Som

Worldwide State-of-the-art

Conclusion

Who are the players?
Are we ahead or behind?

A pot of honey...

CNRS

NTT

UniS
University of Surrey
Guildford

AMO GmbH

KAIST

intel.

leti

LUXTERA

Kungl Tekniska Högskolan

MIT

ATI Advanced Technology Institute

LPM

TU Delft

IBM

freescale semiconductor

Universitat Politècnica de València

Yokohama National University
横浜国立大学

KIST

DARPA

Kyoto University

University of Glasgow

COM•DTU

MESA+

University of Twente
The Netherlands

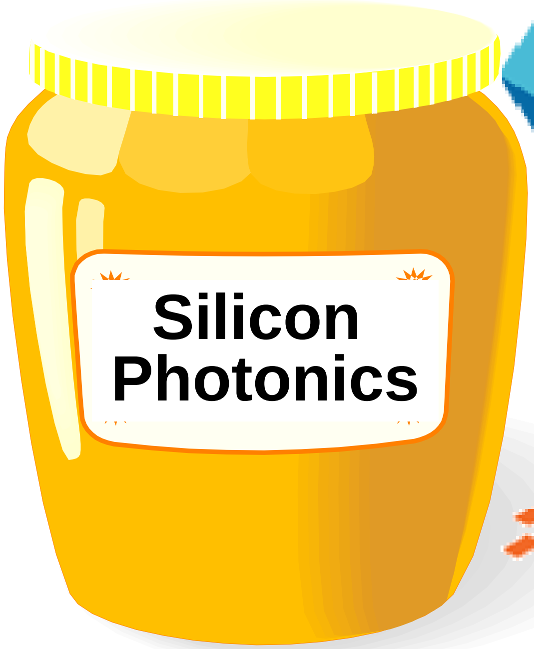
UCLA

PHILIPS

RWTH AACHEN

Universiteit Gent

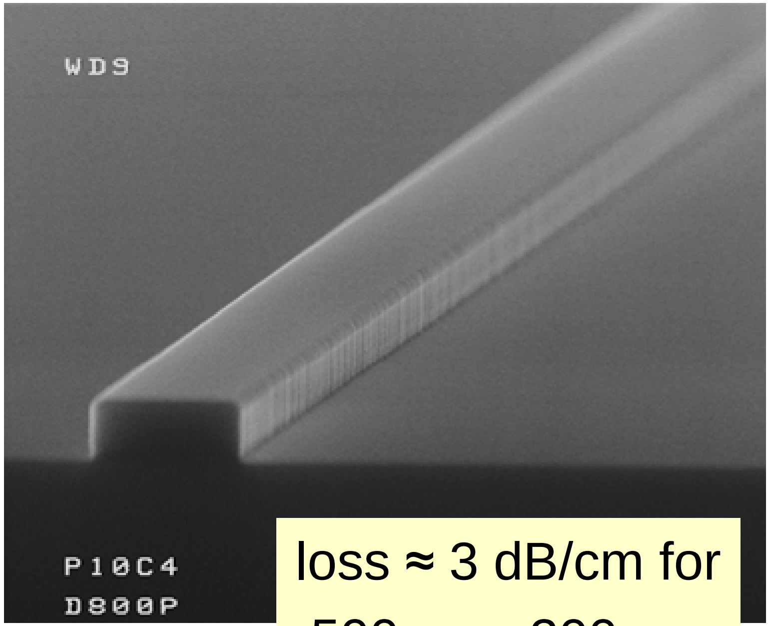
imec



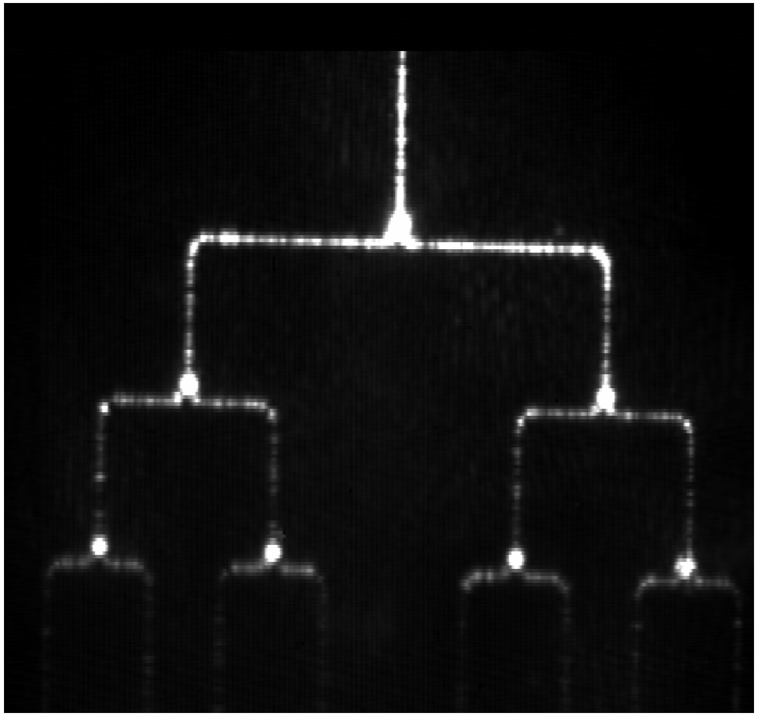
LETI: SOI waveguides

SOI ridge waveguides:

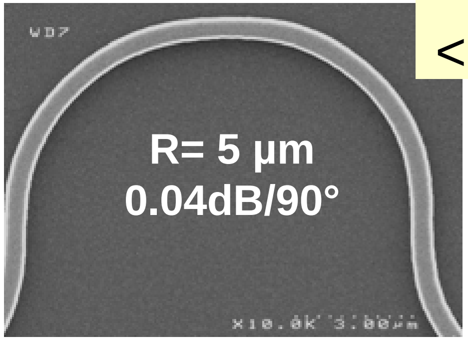
- 500 x 200nm
- 3dB/cm propagation losses



loss ≈ 3 dB/cm for
500nm x 200nm



Imbalance on distribution
<0.5 dB/cm

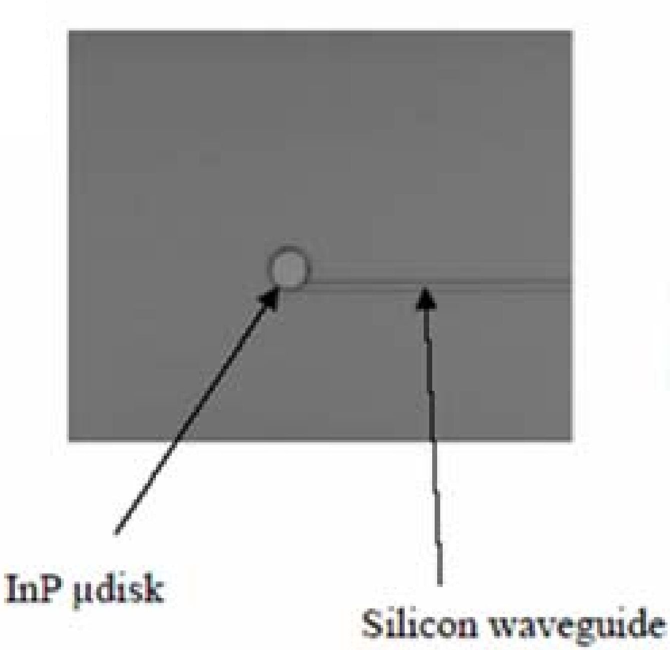


R= 5 µm
0.04dB/90°

Photonic Wire devices

leti

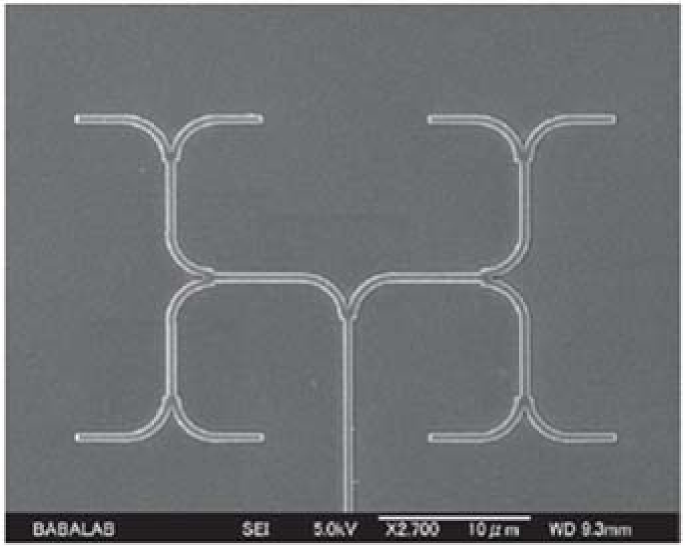
- Fabricated by a 200mm line and 193nm lithography
- integration of InP on SOI
- integration of Ge detectors
- SOI ridge waveguides (~0.4dB/cm)
- Low-T Amorphous Si waveguides
- InP processing
- Coupling InP microlaser to SOI photonic wire



Yokohama National University

横浜国立大学 Yohohama

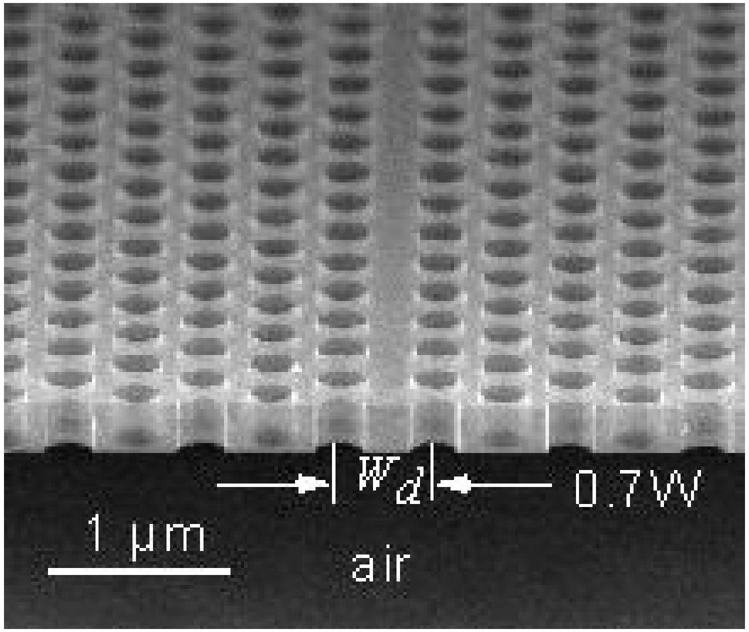
- Fabrication with g-line/i-line
- High propagation losses
- AWGs, Crossings, Splitter trees



Photonic Crystals

NTT

- E-beam lithography
- Low propagation losses: 6dB/cm
- Low-loss interface to fiber



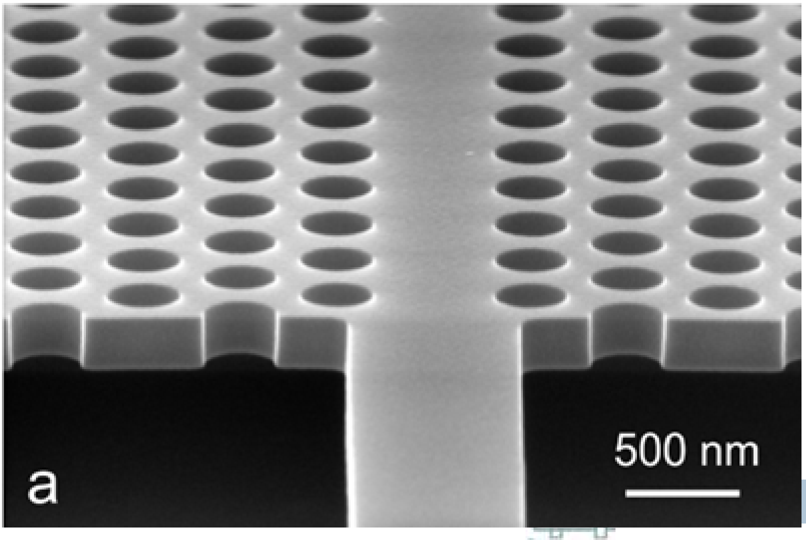
IBM

- In-house CMOS processes
- e-beam lithography is the only out-of-the-line step
- Photonic crystals: low propagation losses
- Slow light in Photonic crystals (Nature, 3/11)


nature

SILICON ENHANCED

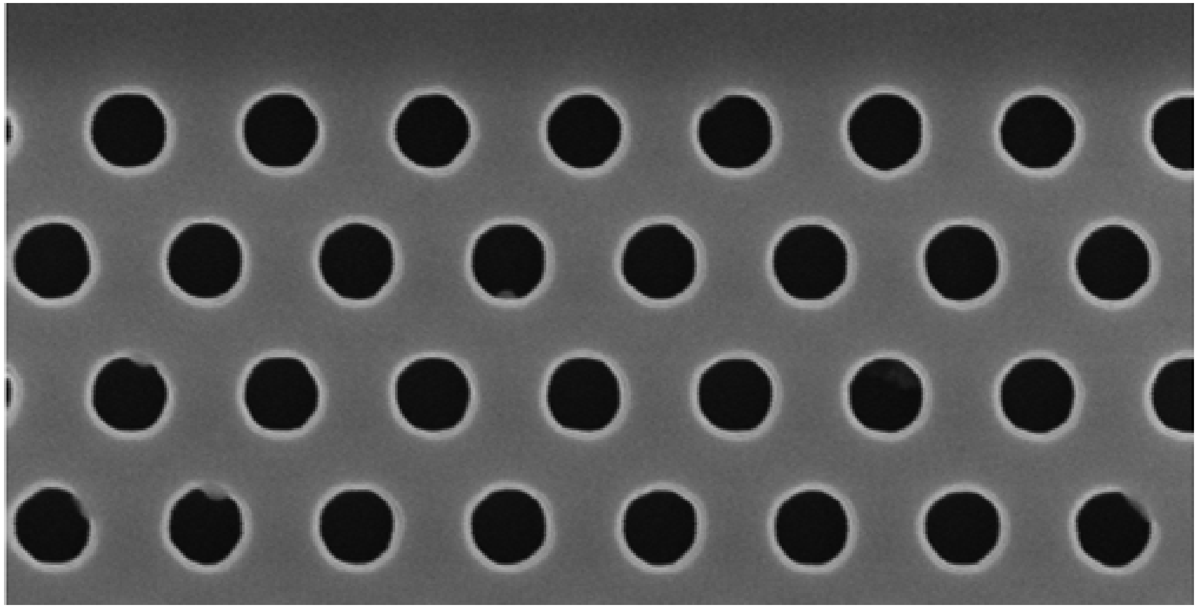
A chip to control the speed of light



Saint-Andrews + INTEL

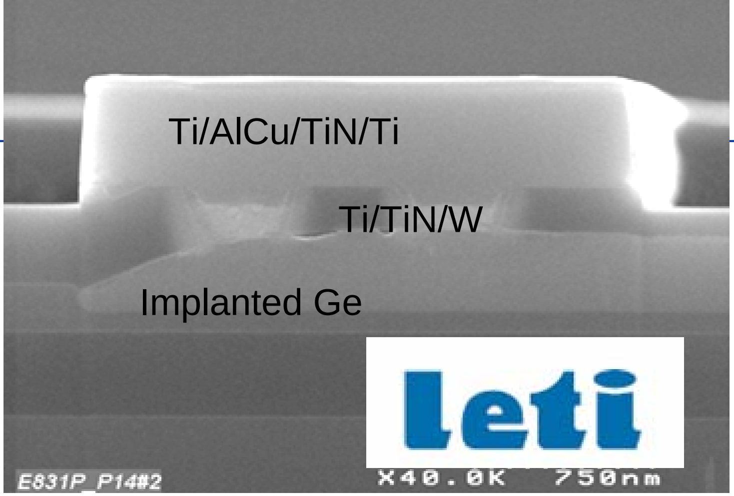
Photonic Crystals with 193nm lithography

- Pitch = 420nm, diameter = 195nm
- No observable proximity effects
- Propagation loss: 14dB/cm



Settle et al, OpEx 14(6) - p2440 (March 2006)

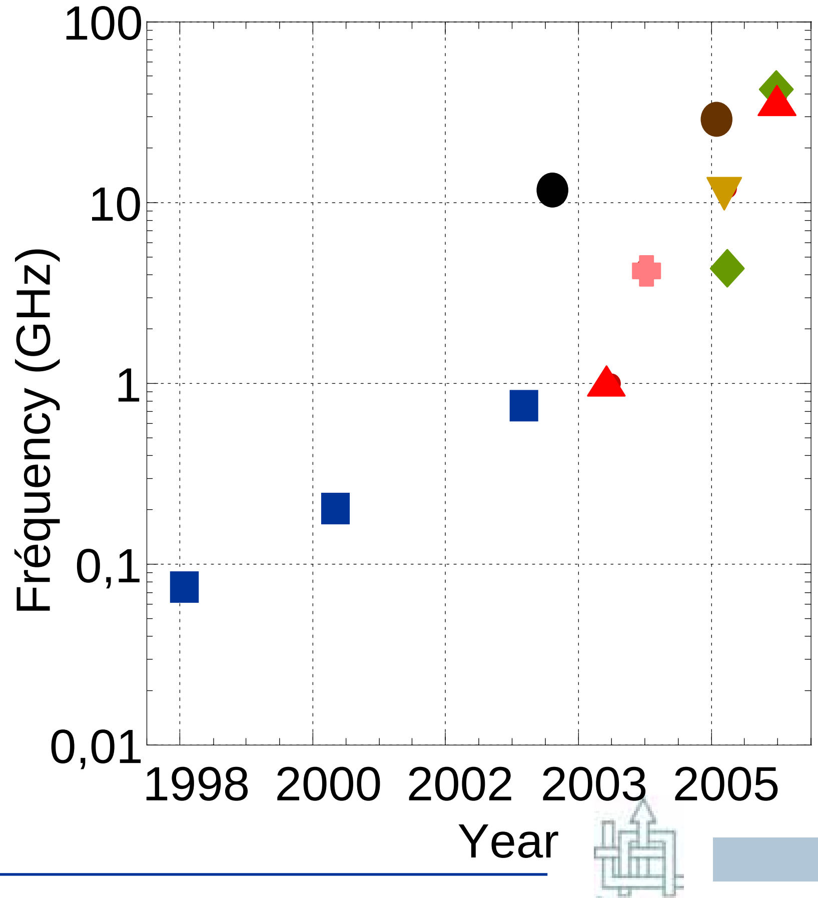
Ge Photodetectors



Germanium on Silicon

- p-i-n photodiode
- coupled to waveguide

Plotted: Speed evolution in recent years



■ *Colace, Massini & al., Univ. Rome*

✚ *Oh & al.,Univ.Texas*

● *Dehlinger & al., Infineon and IBM*

◆ *Jutzi & al., Univ. Stuttgart*

Si waveguide

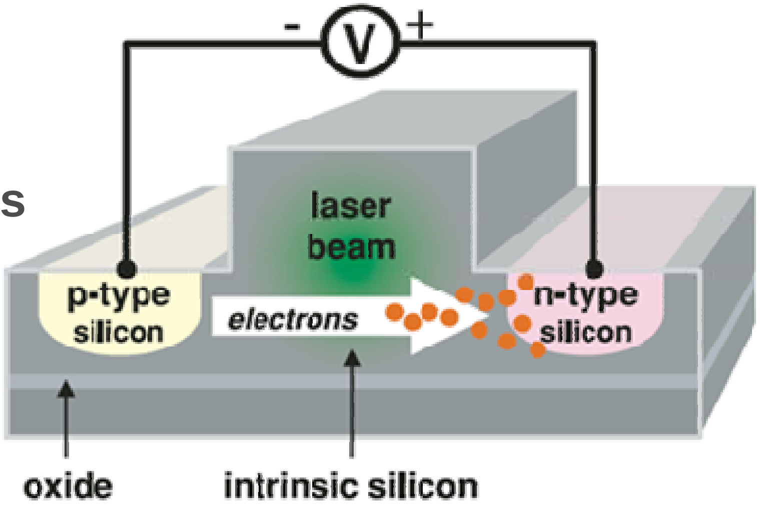
▼ *Dosonmu & al., Univ. Boston and MIT*

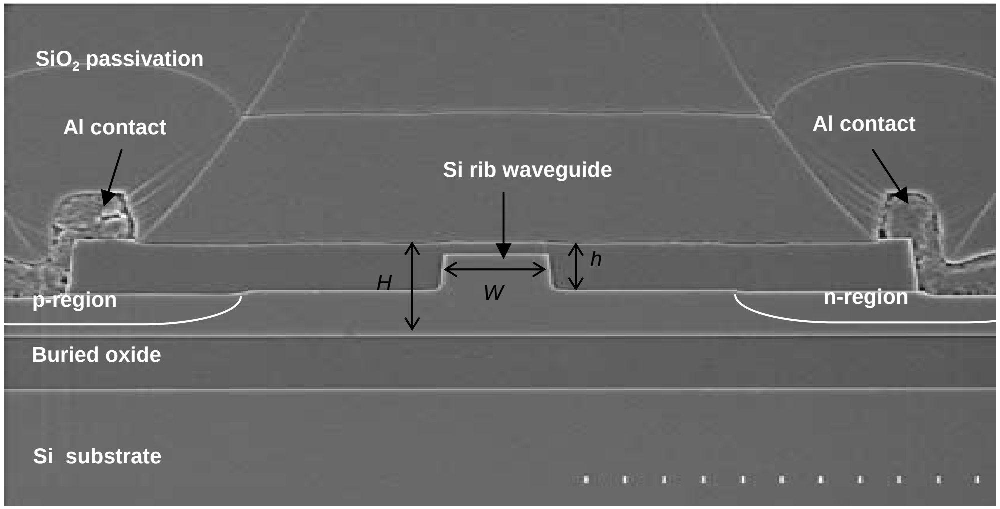
▲ *CEA-LETI & IEF*

Silicon sources and modulators

Waveguides integrated in lateral p-(i)-n diode

- Optical modulator @ 10GHz:
  modulate using current injection
- Silicon CW Raman laser:
  extract free carriers with reverse bias



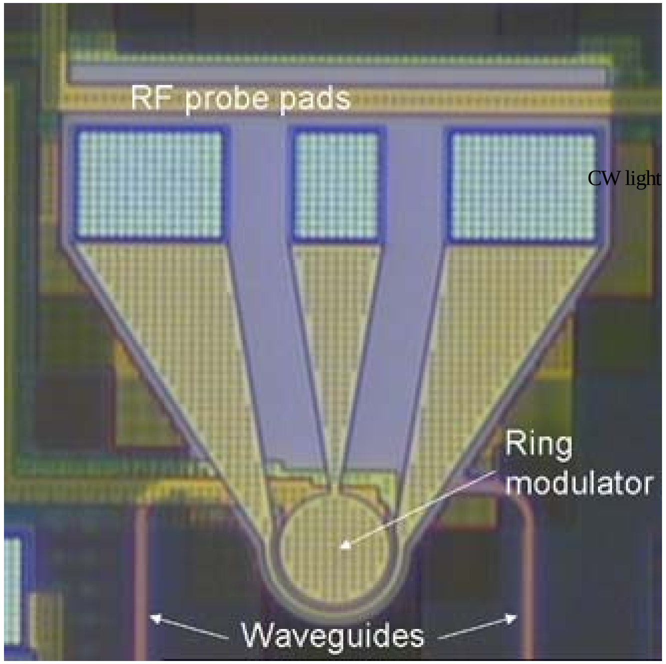


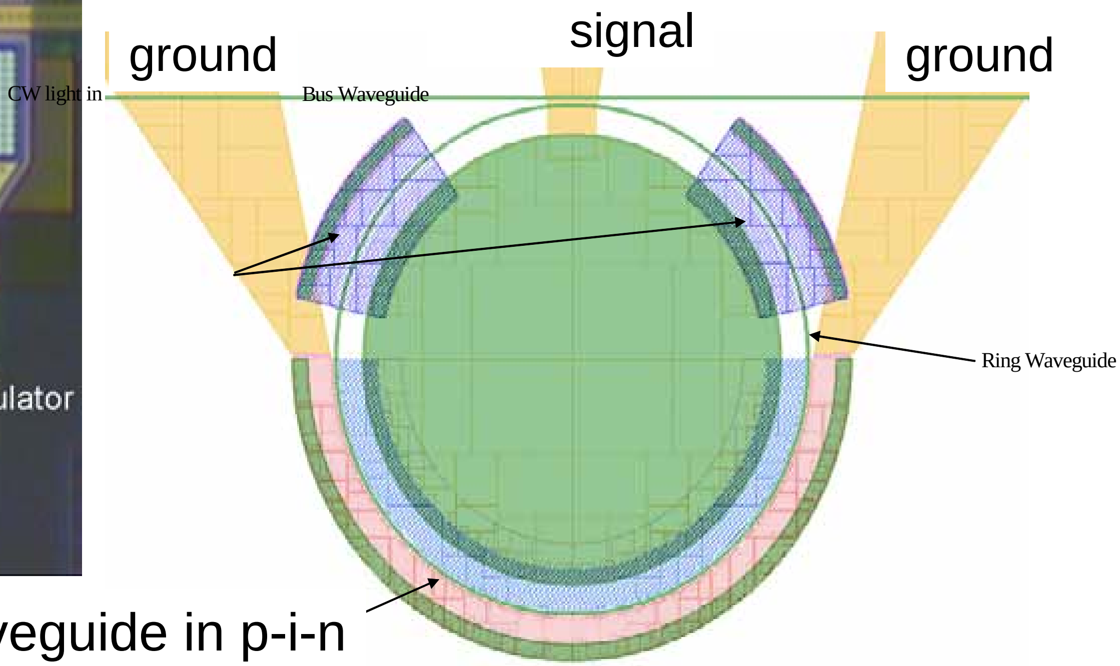
H = 1.55 µm h = 0.7 µm W = 1.5 µm

Ring modulator

Ring resonator in p-i-n junction

- Carrier injection
- Change refractive index
- Change resonance





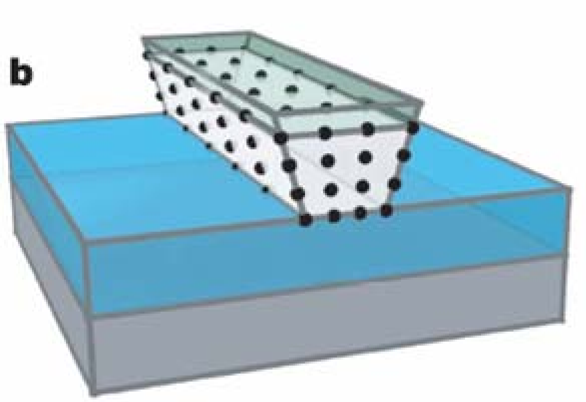
Strained Silicon

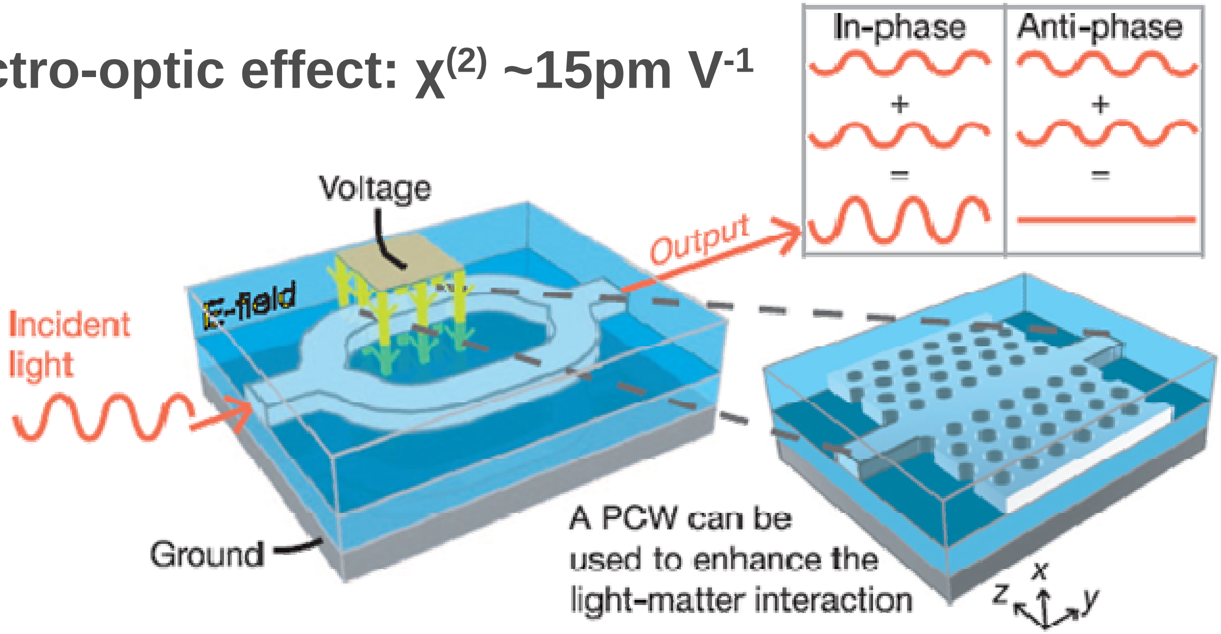
Silicon:

- centrosymmetric crystal structure
- no electro-optic effect

Apply Si_3N_4 strain layer

- Deform crystal structure
- Induce electro-optic effect: $\chi^{(2)}$ ~15pm V^{-1}



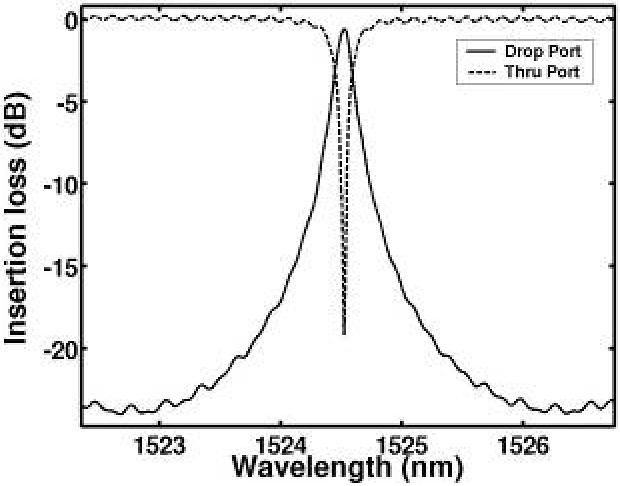


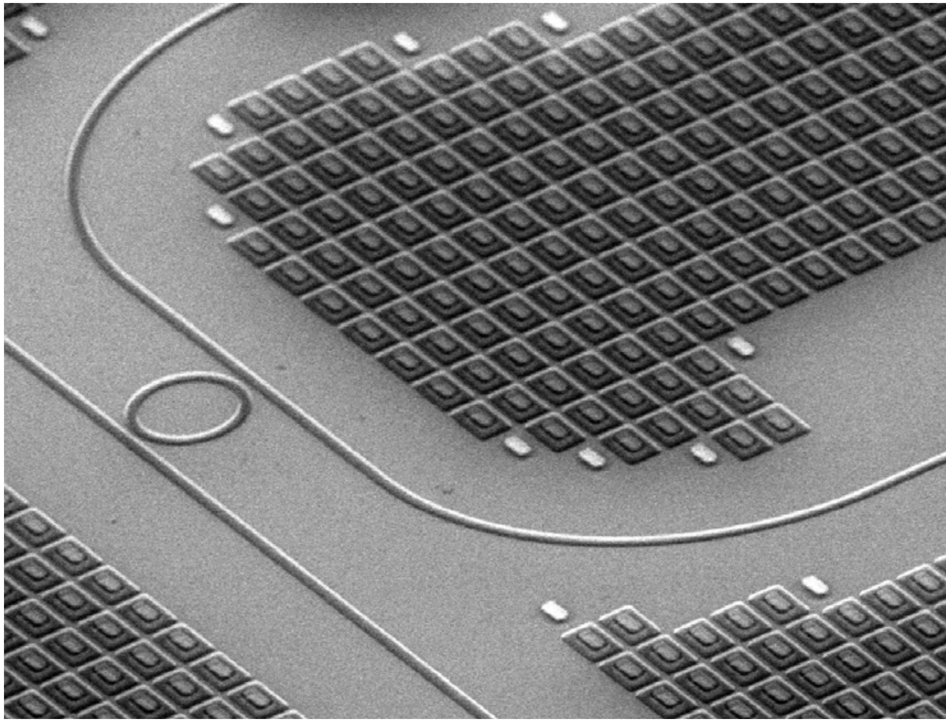
Jacobson et al., nature 04706 (May 2006)

Integration with CMOS

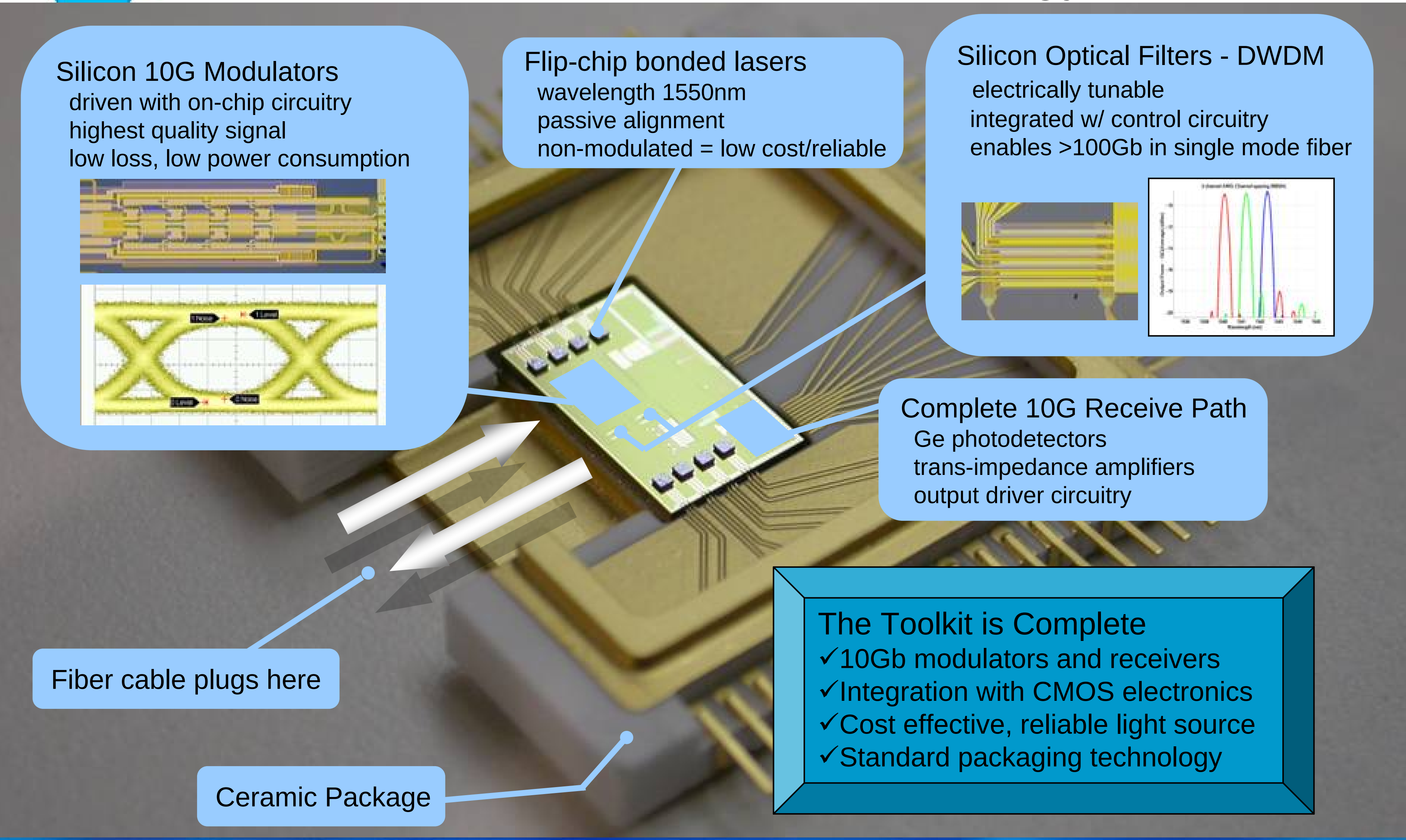
Luxtera

- Fabless Silicon Photonics (Fabrication by Freescale)
- Integration of CMOS and photonic circuits:
  Waveguides are defined together with transistor gates
- Low-loss rib waveguide
- Grating fiber couplers





Luxtera CMOS Photonics Technology



Silicon 10G Modulators
- driven with on-chip circuitry
- highest quality signal
- low loss, low power consumption

Flip-chip bonded lasers
- wavelength 1550nm
- passive alignment
- non-modulated = low cost/reliable

Silicon Optical Filters - DWDM
- electrically tunable
- integrated w/ control circuitry
- enables >100Gb in single mode fiber

Complete 10G Receive Path
- Ge photodetectors
- trans-impedance amplifiers
- output driver circuitry

Fiber cable plugs here

Ceramic Package

The Toolkit is Complete

✓10Gb modulators and receivers
✓Integration with CMOS electronics
✓Cost effective, reliable light source
✓Standard packaging technology

Objectives

- Si nanophotonics with CMOS processes
- Application-specific EPIC
- New photonic devices in Si
  (lasers, wavelength converters, amplifiers, ...)

Partners

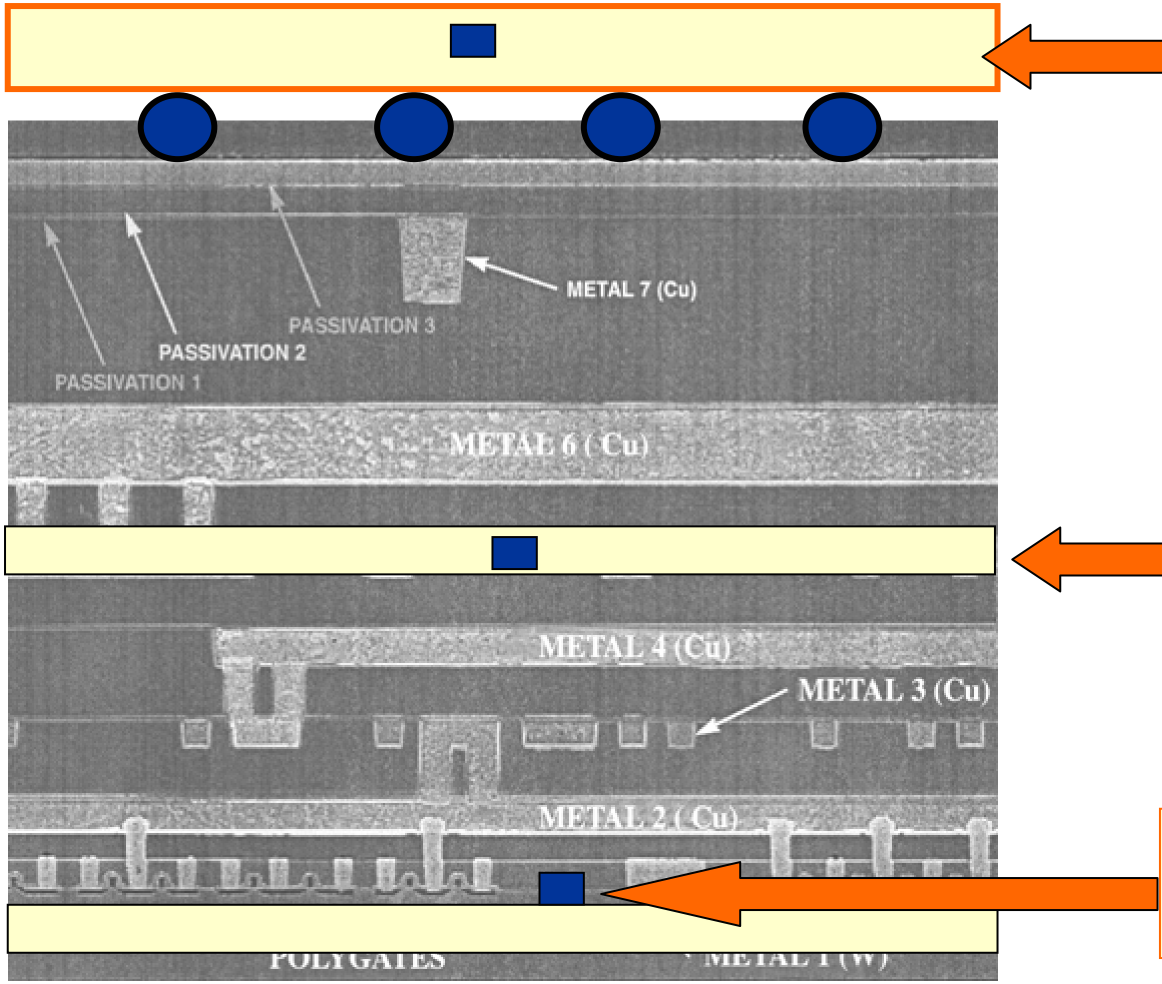
- MIT
- Luxtera
- Freescale

Recent results:

- Low-loss waveguides in SOI, made in BAe fab

www.darpa.mil/mto/epic

Photonics with CMOS ?



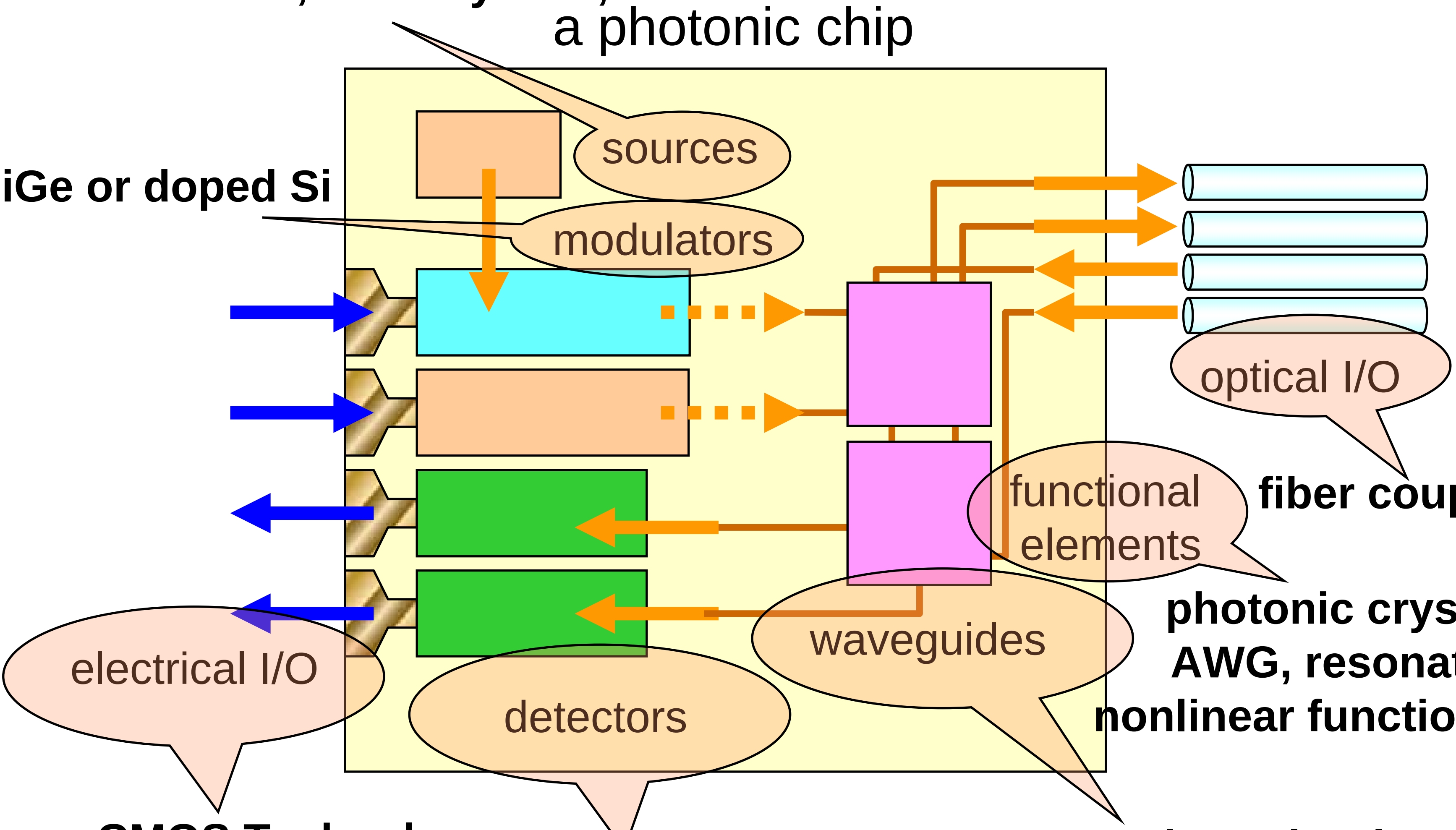
Photonic IC (PIC) flip-chipped on Electronic IC (EIC)

Photonic layer embedded between metallisations

Combined front-end fabrication

Source: IBM Processor on SOI 0.12µm

What is possible in Silicon?



raman laser, nanocrystals, ...

SiGe or doped Si

fiber couplers

photonic crystals
AWG, resonators
nonlinear functions?

CMOS Technology

Germanium PD

photonic wires

Conclusion

Silicon is great for nanophotonics

- passive waveguide structures
- photonic crystals
- recently demontrated: modulators, detectors, sources

Many impressive results

- good waveguides
- wavelength-selective functions
- based on CMOS technologies

A strong international interest

- Universities: MIT, Kyoto, UCLA, DTU, Valencia, ...
- Commercial: INTEL, IBM, NTT, Luxtera, AMO, ...

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  - *IST-PICMOS*
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Any questions?...