Silicon Photonics

Roel Baets
Ghent University – IMEC
roel.baets@ugent.be
www.photonics.intec.ugent.be

ESA February 9 2006

Acknowledgements

- The Photonic Research Group at Ghent University – IMEC
- The European Union
  - *IST-PICCO*
  - *IST-PICMOS*
  - *IST-ePIXnet*
- The European Space Agency
- The Belgian IAP-PHOTON network
- The Flemish Institute for the industrial advancement of Scientific and Technological Research (IWT)
- The Flemish Fund for Scientific Research (FWO-Vlaanderen)
- The Silicon Process division at IMEC
- The P-line at IMEC

Outline

Silicon Photonics: why and how?

Passive wavelength routers in Silicon

Active photonic functions in Silicon

Silicon photonics: what for?

Silicon Photonics: why and how?

Why?

- Functionality + performance
- Technology
- Cost

How?

- Wafer-level fabrication
- Packaging

Silicon photonics

Functionality and performance:

spectacular breakthroughs in last 2 years

- low loss waveguides (IMEC, NTT, IBM…)
- compact wavelength routers (IMEC…)
- ultra-compact microcavities (U. Kyoto…)
- >>10 Gb/s receivers (LETI…)
- 10 Gb/s modulators (INTEL, LUxtera…)
- Raman Silicon laser (INTEL…)
- (velocity tunable) slow light (IBM…)
- all-optical switching + λ-conversion (NICT+IMEC…)
- integration with CMOS (Luxtera…)

EPIC ELECTRONIC & PHOTONIC INTEGRATED CIRCUITS

Objectives

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

Partners

- MIT
- Luxtera
- Sun
- Freescale

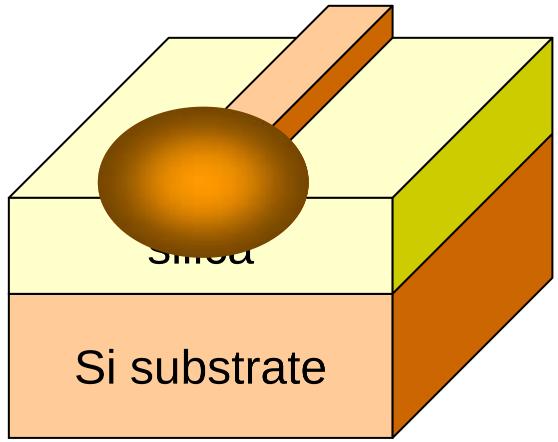
Budget: 12M$

www.darpa.mil/mto/epic

Nanophotonic waveguides

Silicon on Insulator

- **Transparent at telecom wavelengths (1.55μm and 1.3μm)**
- **High refractive index contrast**
  - **in-plane: 3.45(Si) to 1.0 (air)**
  - **out-of-plane: 3.45 (Si) to 1.45 (SiO_2)**
- **Typical dimensions:**
  - **Thickness: 200 nm**
  - **Width: 500 nm**
  - **Required accuracy: 1-10 nm**
- **Compatible with CMOS processes**



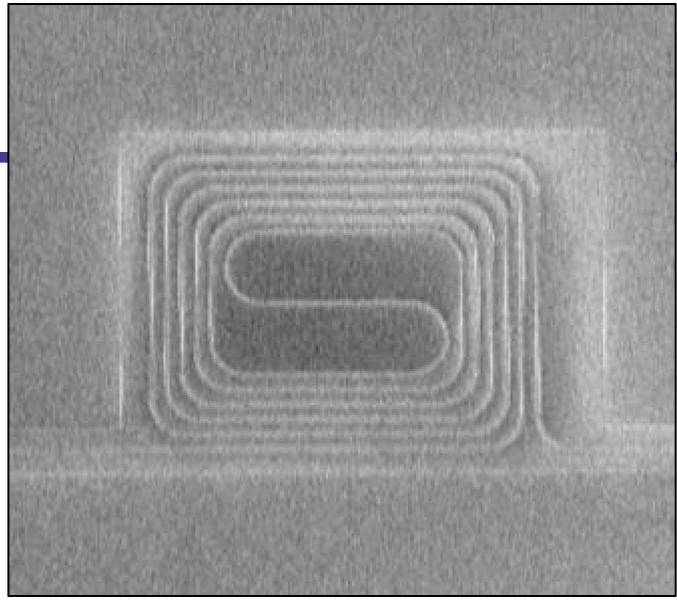
SOI-nanophotonic wires

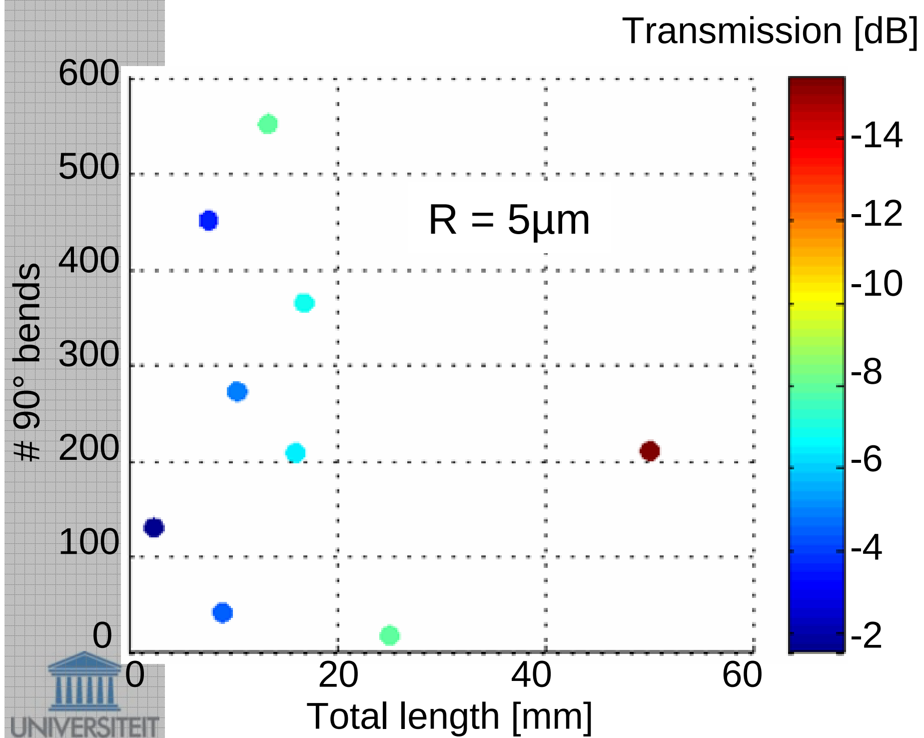
Group	Date	h [nm]	w [nm]	loss [dB/cm]	BOX [um]	top clad	Fab.
IMEC	Apr. '04	220	500	2.4	1	no	DUV
IBM	Apr. '04	220	445	3.6	2	no	EBeam
Cornell	Aug. '03	270	470	5.0	3	no	EBeam
NTT	Feb. '05	300 200	300 400	7.8 2.8	3	yes	EBeam
Yokohama	Dec. '02	320	400	105.0	1	no	EBeam
MIT	Dec. '01	200	500	32.0	1	yes	G-line
LETI / LPM	Apr. '05	300 200	300 500	15.0 5.0	1	yes	DUV
Columbia	Oct. 03	260	600	110.0	1	yes	EBeam
NEC	Oct. '04	300	300	19.0	1	yes	EBeam

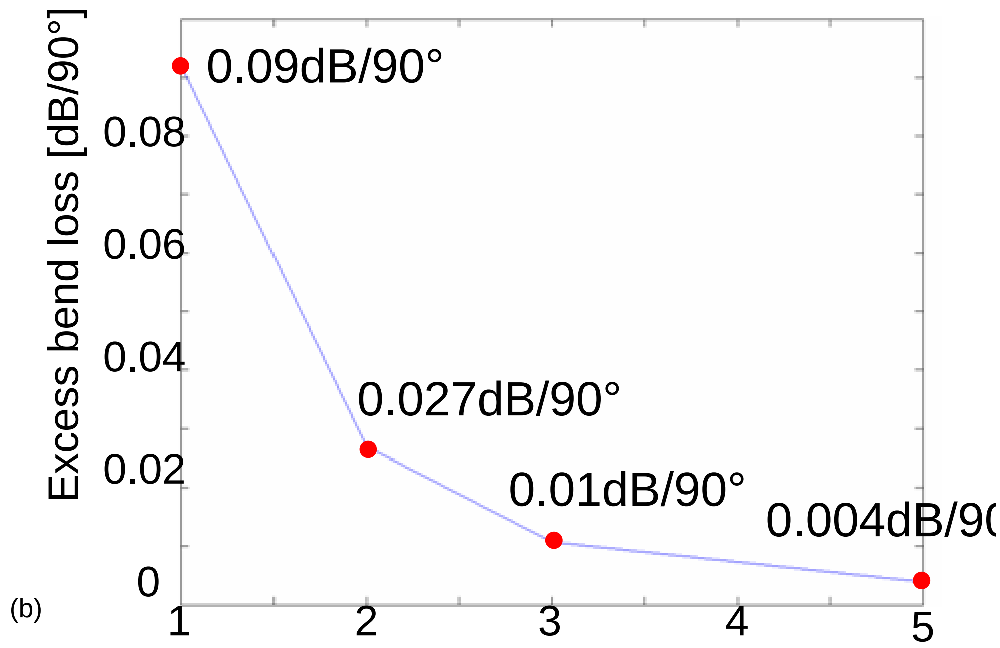
Waveguide bends

Spirals

- **Long waveguides (up to 50mm)**
- **Many bends (up to 560)**







Bends

Group	h [nm]	w [nm]	Radius [um]	Loss [dB/90]	Note
IBM	220	445	1.0 2.0 5.0	0.086 0.013 0	20 bends
IMEC	220	500	1.0 2.0 5.0	0.09 0.027 0.004	> 500 bends
NTT	300	300	2.0 3.0	0.46 0.17	24 bends
Yokohama	320	400	1.0	3	
MIT	200	500	1.0 resonant	0.5 0.3	12 bends poly-Si
LETI/LPM	220	500	2.0 5.0	0.15 0.05	40 40
Columbia	340	400	resonant	1.3	2 bends

(Table partly from Vlasov, McNab, Opt. Expr. '04, pp1630)

up

Nano ?

- Feature size: a few 100nm
- Required accuracy of features:
- For wavelength-dependent stru

nm-scale wavelength accuracy : O(1nm) dimensional accuracy !

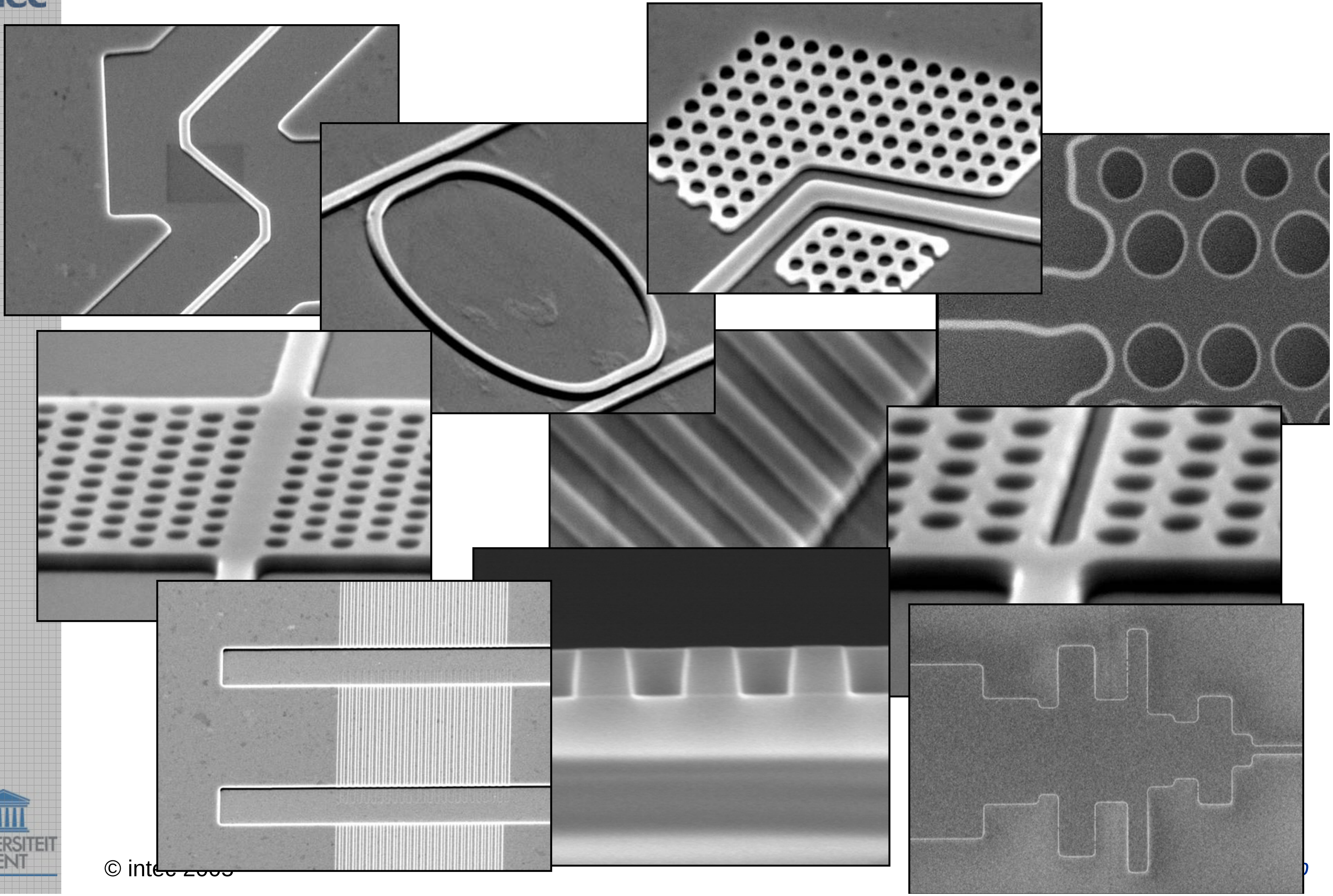
Fabrication ?

- Classical optical lithography → too low resolution
- E-beam lithography, focused ion beam → too slow

➔ Deep UV lithography (used for CMOS)

- 248nm, 193nm
- Fabrication in IMEC CMOS-pilot line
- 200mm wafers

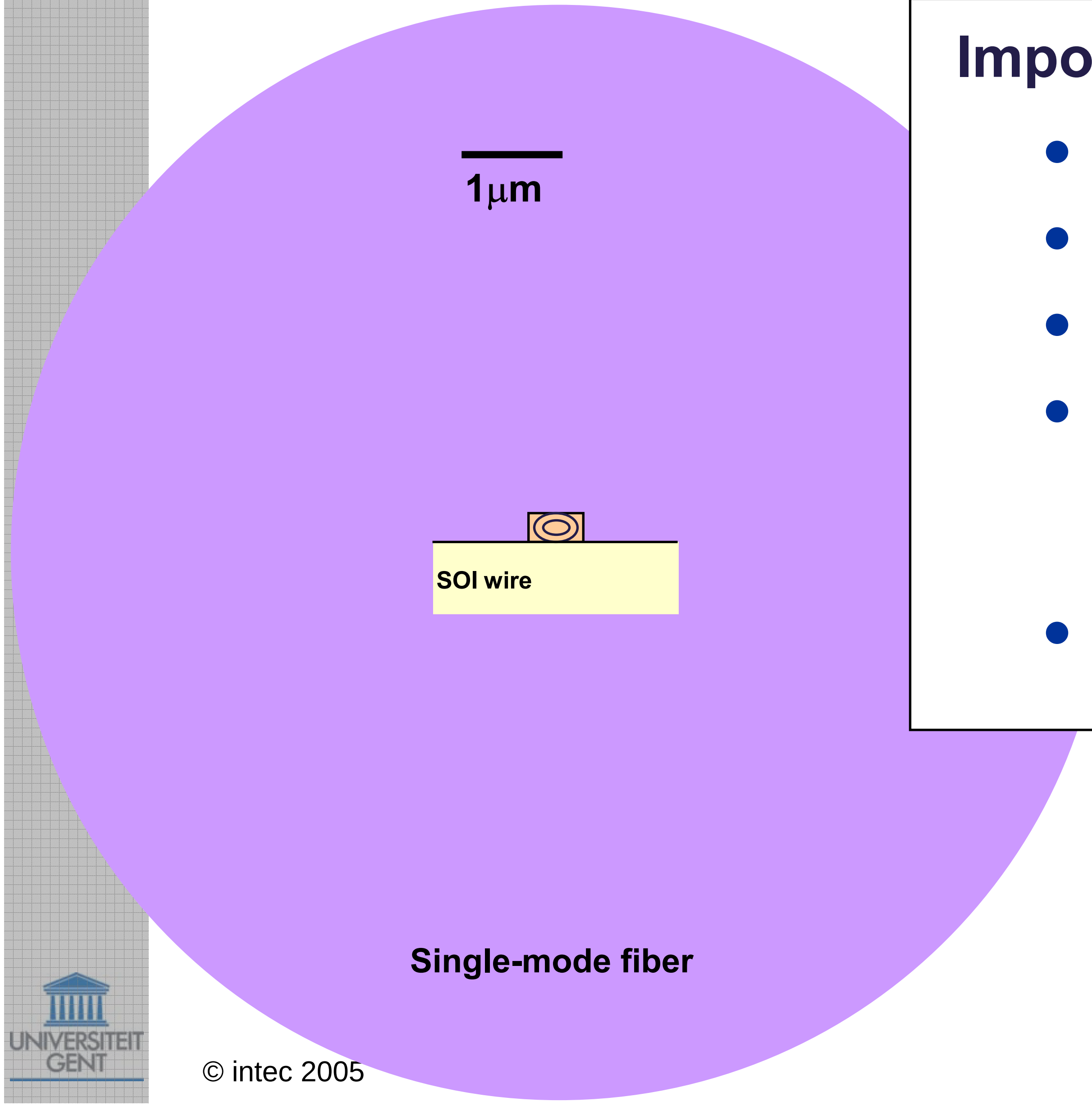
Fabricated Structures



Low cost

- Wafer-scale fabrication on large wafers with high yield
- Wafer-scale testing
- Low cost packaging

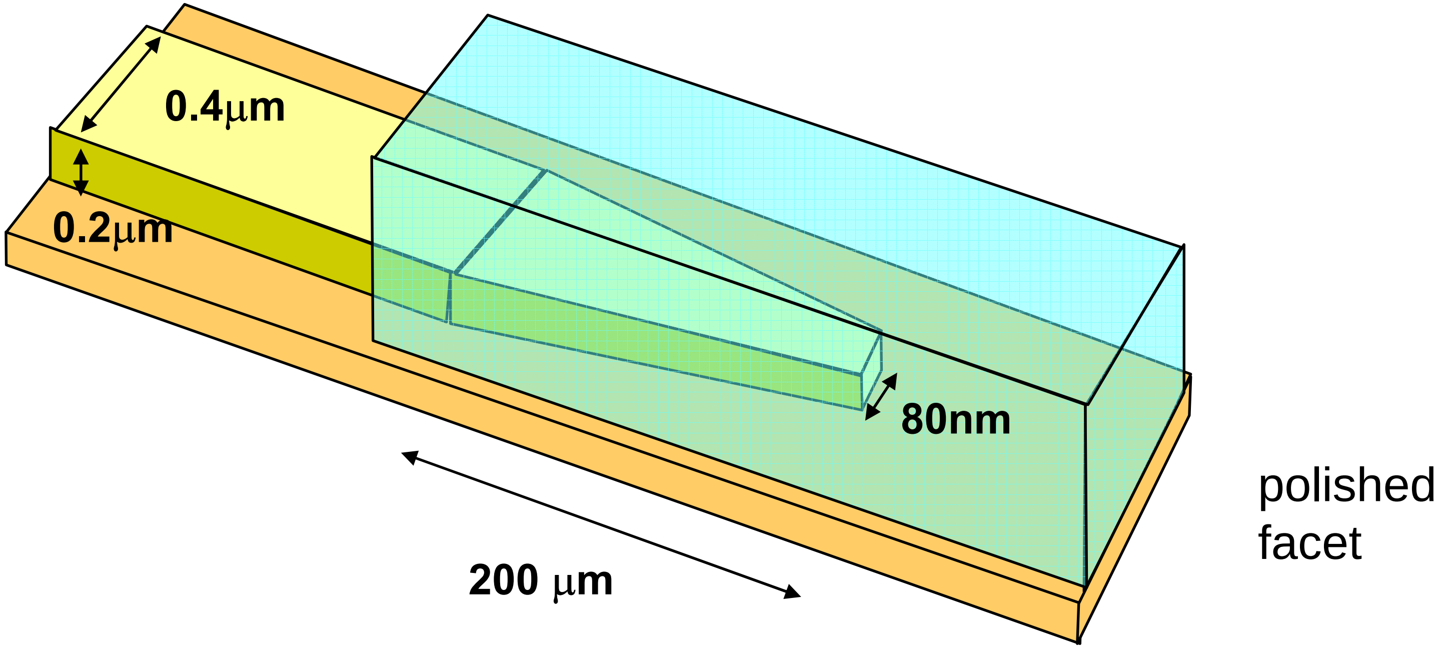
Coupling into SOI nanophotonics



Important:

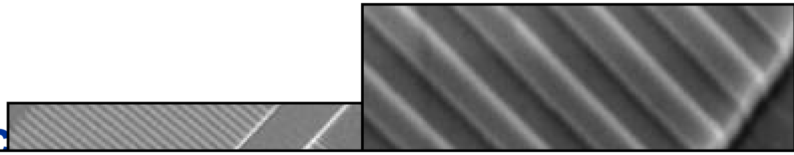
- Low loss
- Large bandwidth
- Coupling tolerance
- Fabrication
  - Limited extra processing
  - Tolerant to fabrication
- Polarization

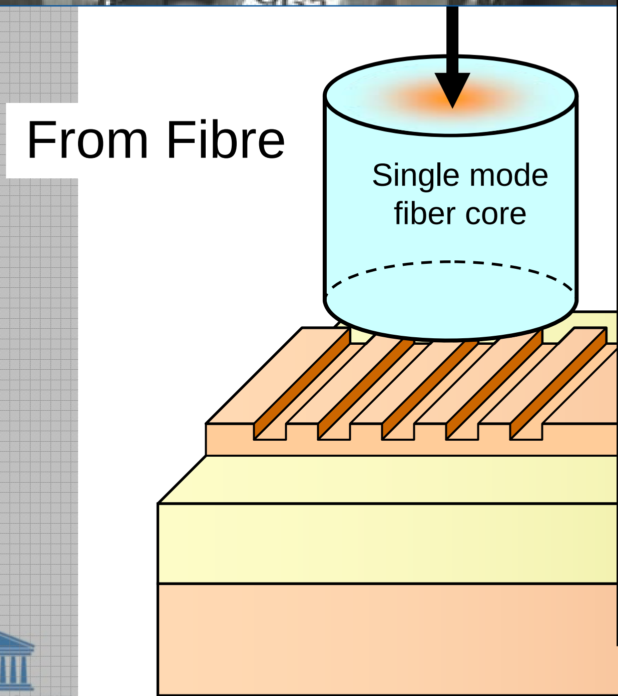
Coupling to fiber – Inverse taper

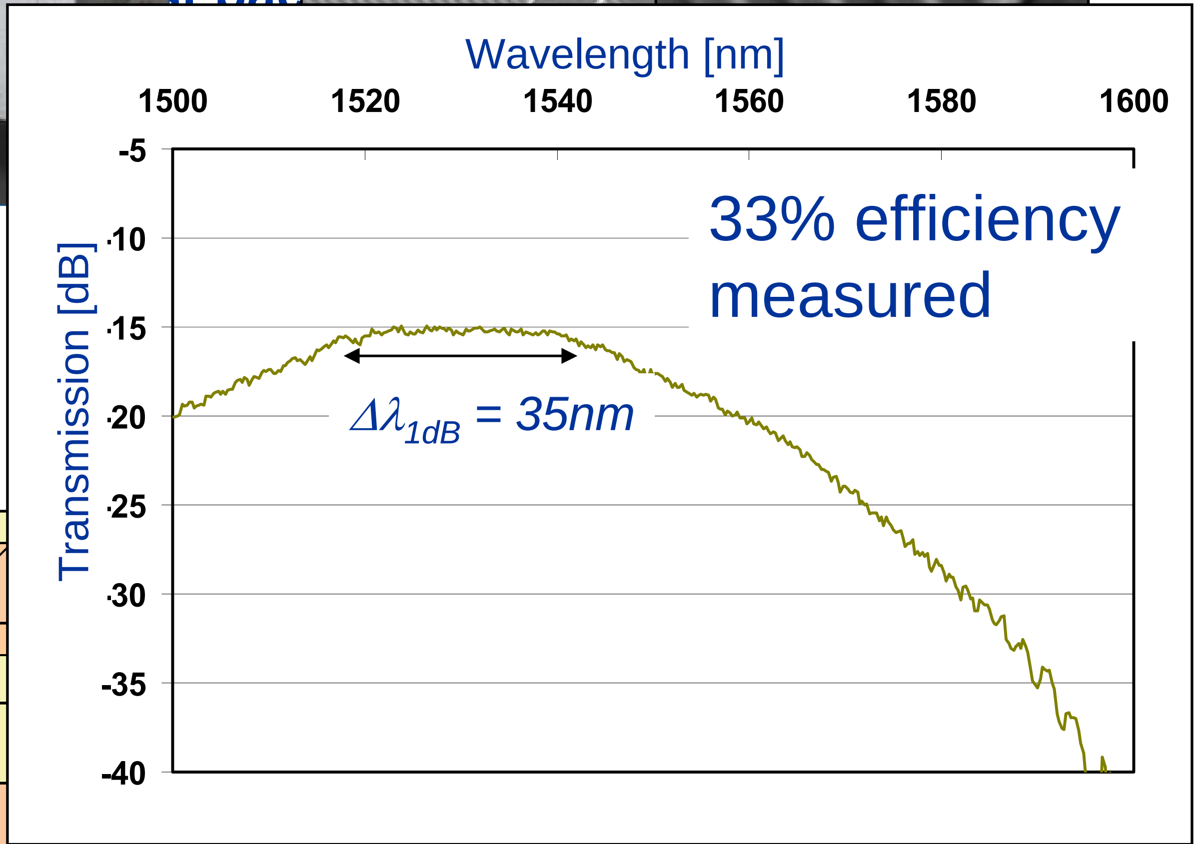


Group	h [nm]	w [nm]	L [um]	tip width [nm]	Cladding Material	Cladding Size	Loss
IBM (e-beam)	220	445	150.0	75.0	Polymer	2x2	< 1dB
Cornell (e-b)	270	470	40.0	100.0	SiO2	?x?	< 4dB
IMEC(DUV)	200	500	175.0	175.0	Polymer	3x1.3	< 2dB
NTT (ebeam)	300	300	200.0	60.0	Polymer/Si3N4	3x3	0.8

Coupling to fiber – Grating coupler

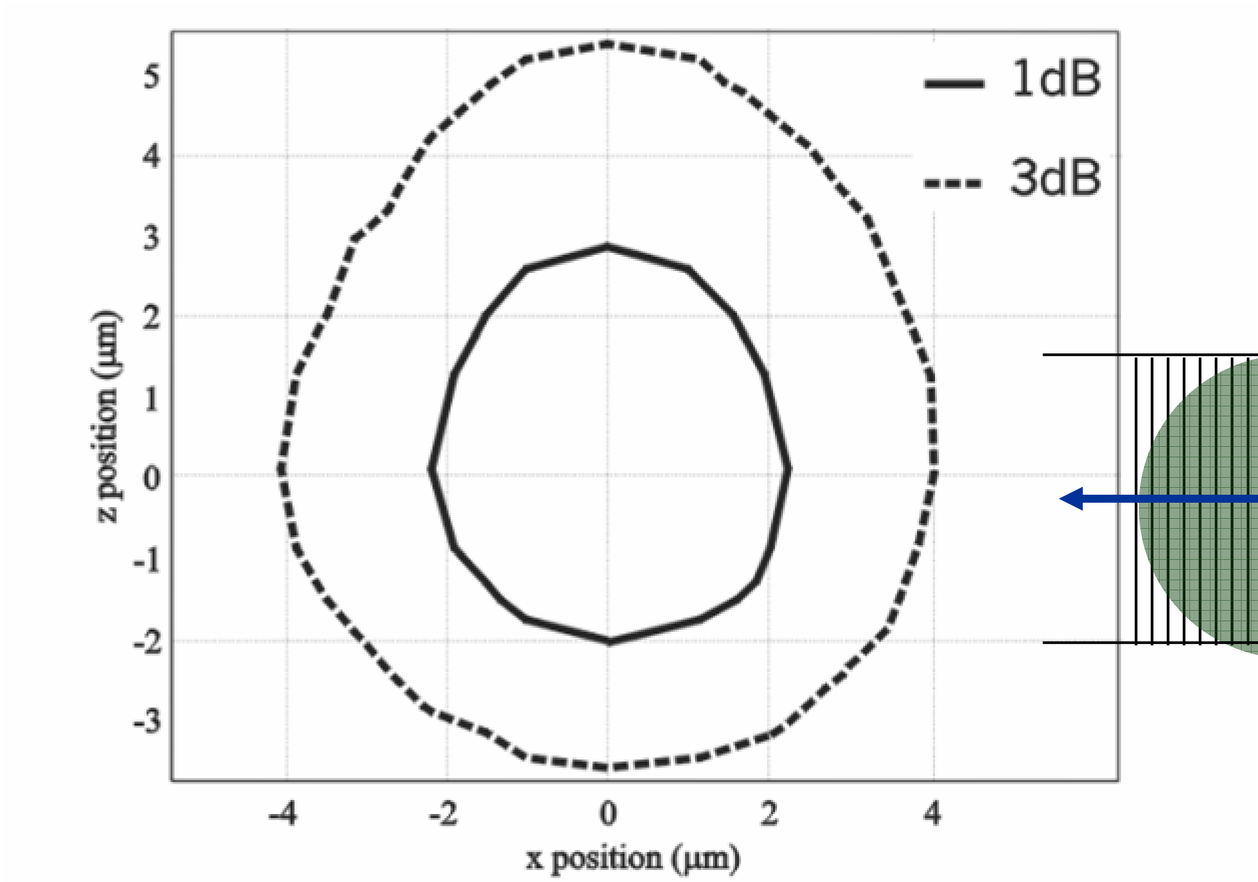


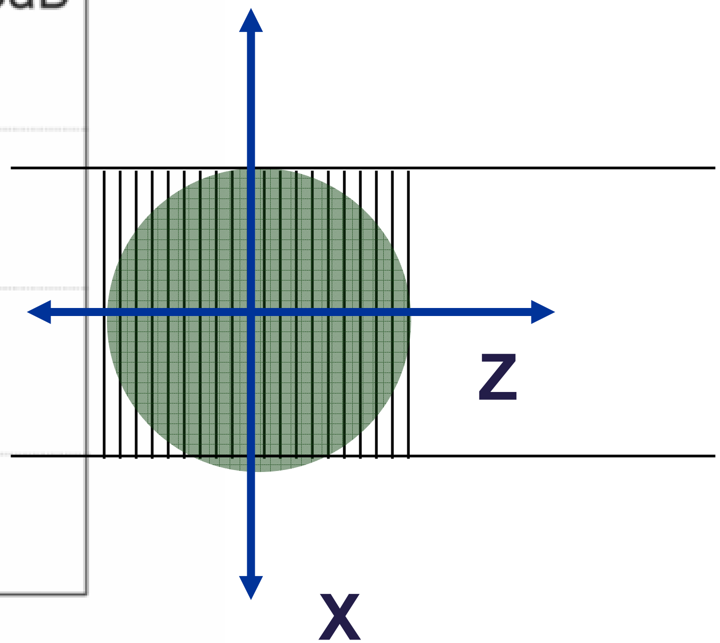




Alignment tolerances

- good alignment tolerances
- measurement of P/P_{max} versus fiber position



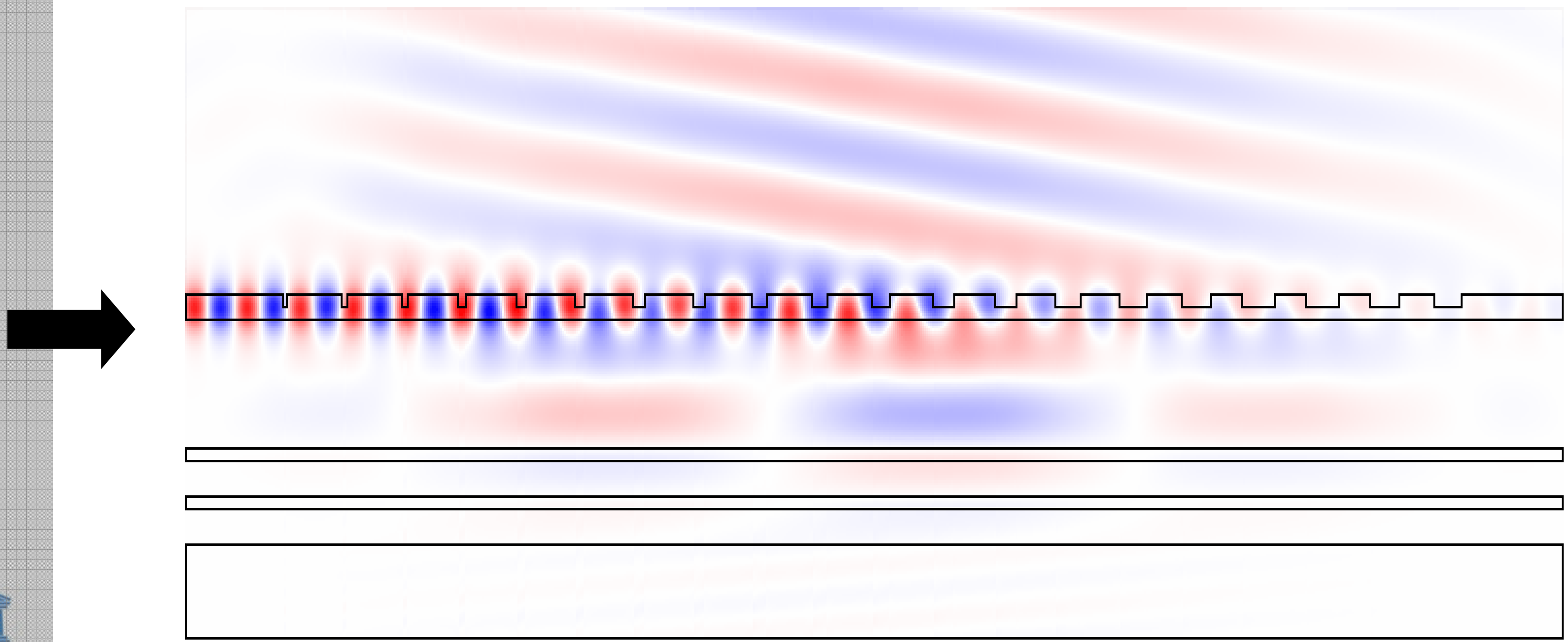


Taillaert et al, JQE 38(7), p. 949 (2002)

Coupling to fiber – Grating coupler

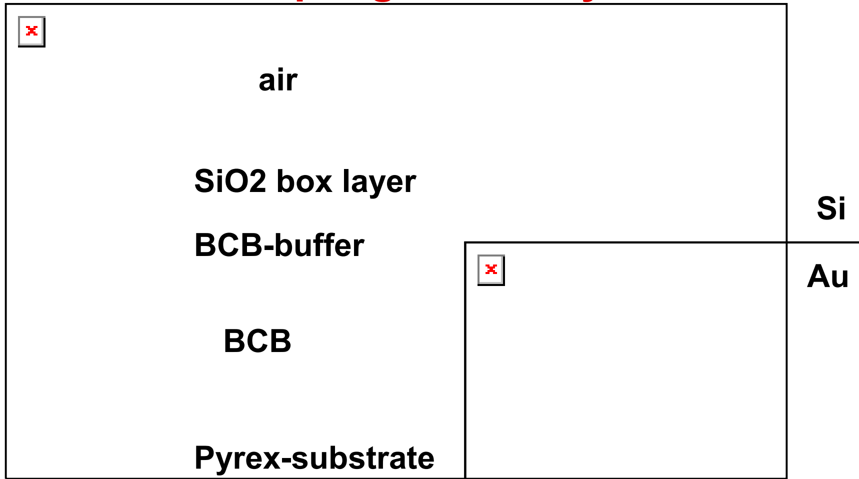
Improved design

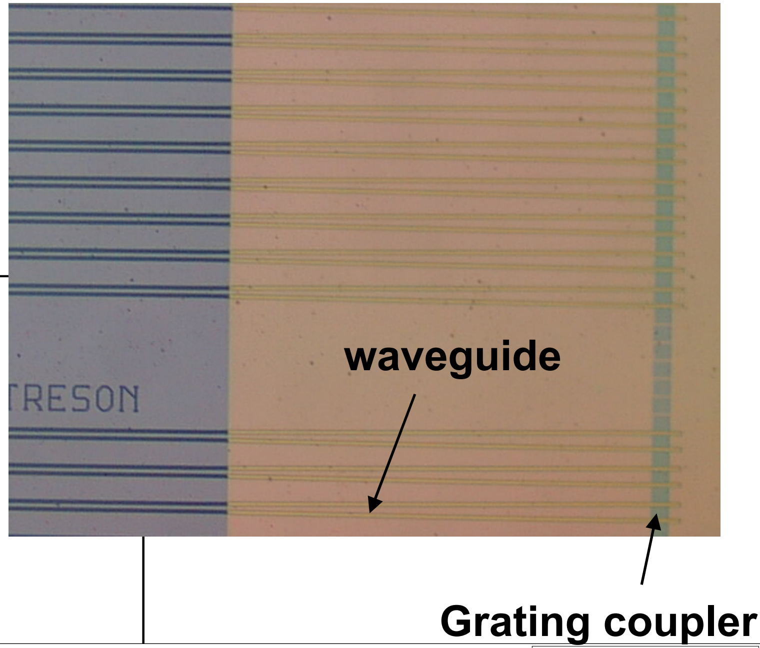
- Apodise grating → efficiency 63%
- Add bottom reflector → efficiency over 90%



Bonded SOI-coupler with gold bottom mirror

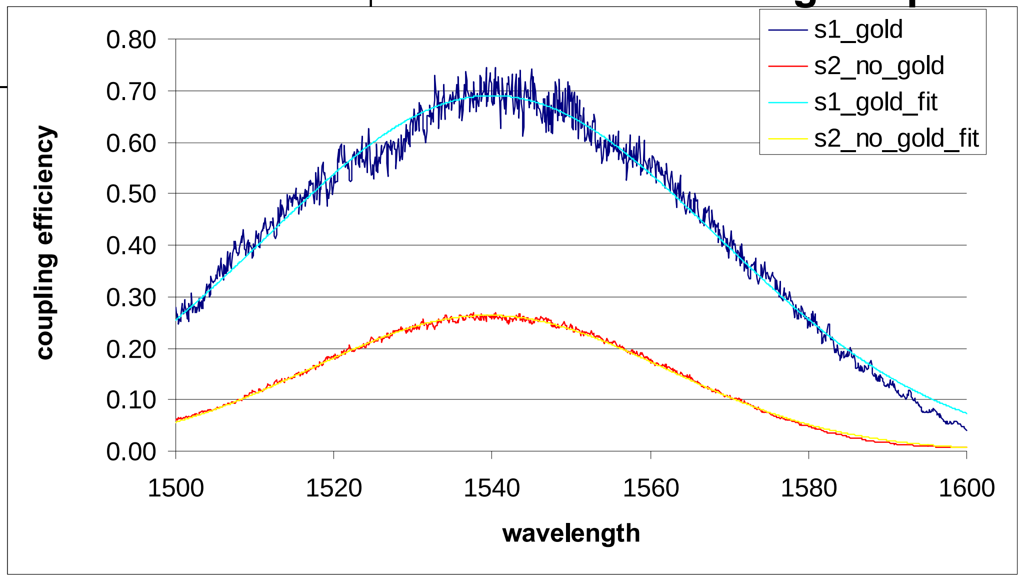
Theoretical coupling efficiency 78%





Measured coupling efficiency:

69% (1.5 dB loss)

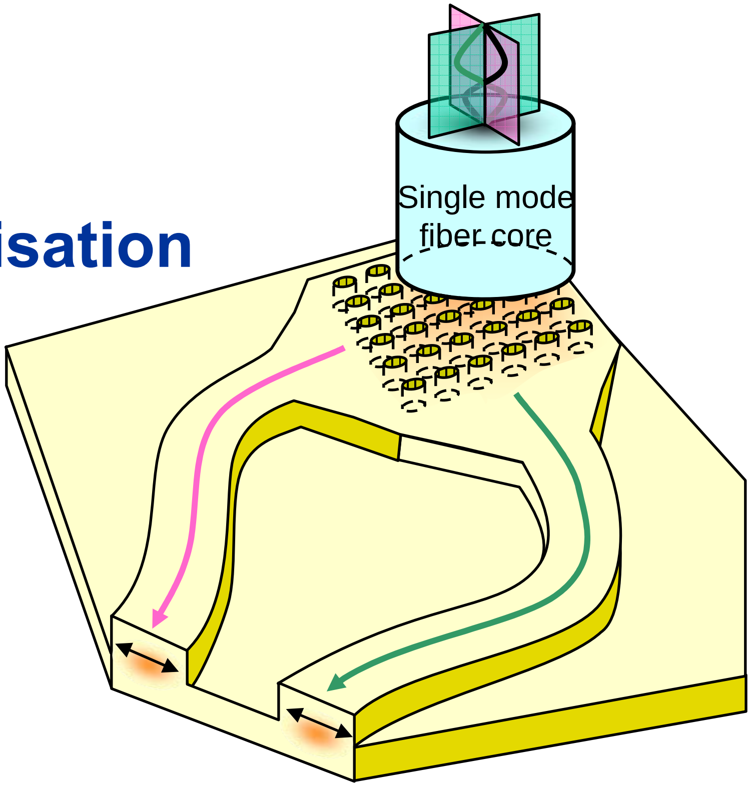


Polarisation problem

Problem: nanophotonic circuits are highly polarisation dependent

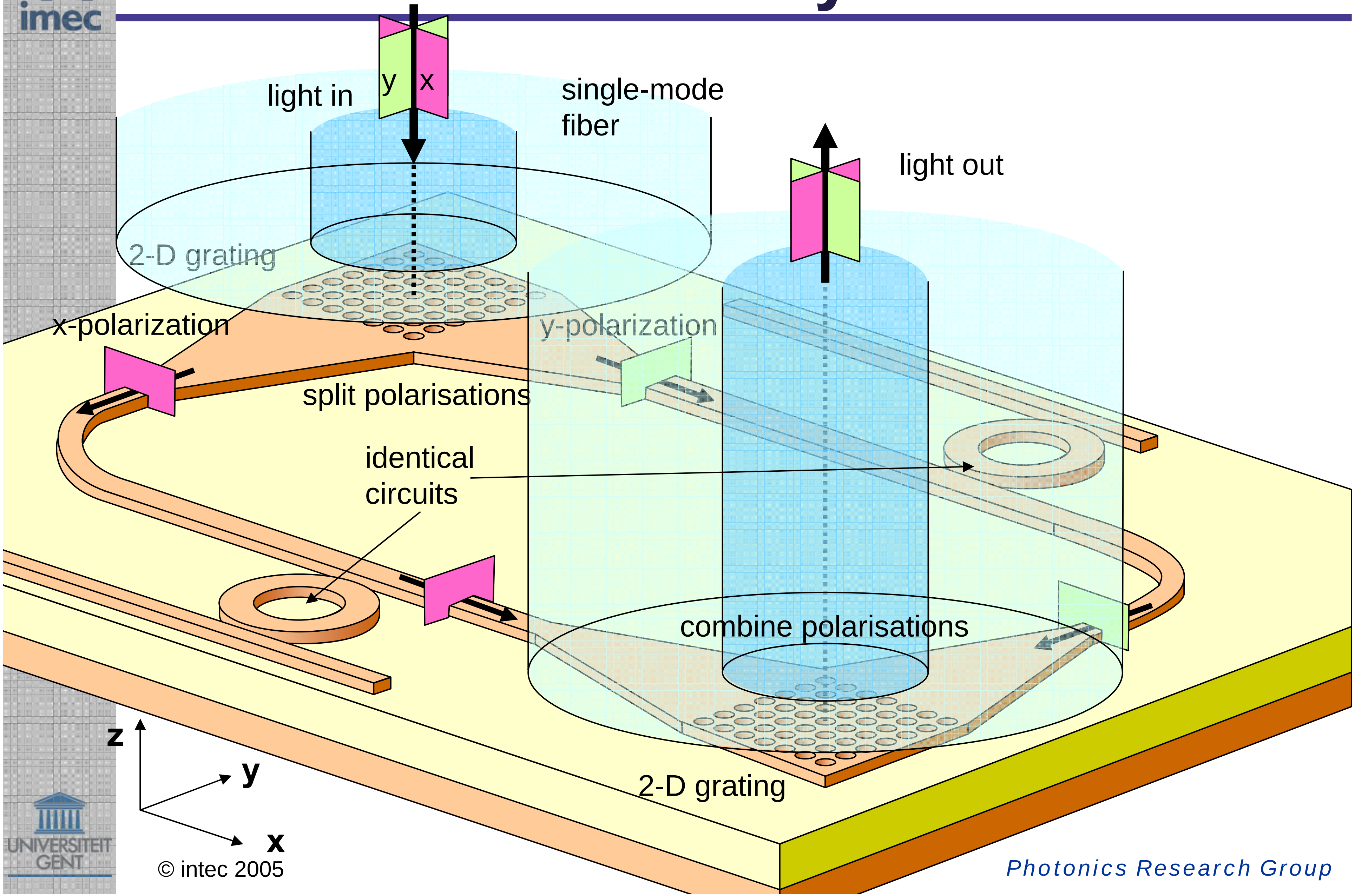
Our solution:

- **2D grating**
- **Couples each fiber polarisation in its own waveguide**
- **In the waveguides the polarisation is the same (TE)**
- **Allows for polarisation diversity approach**

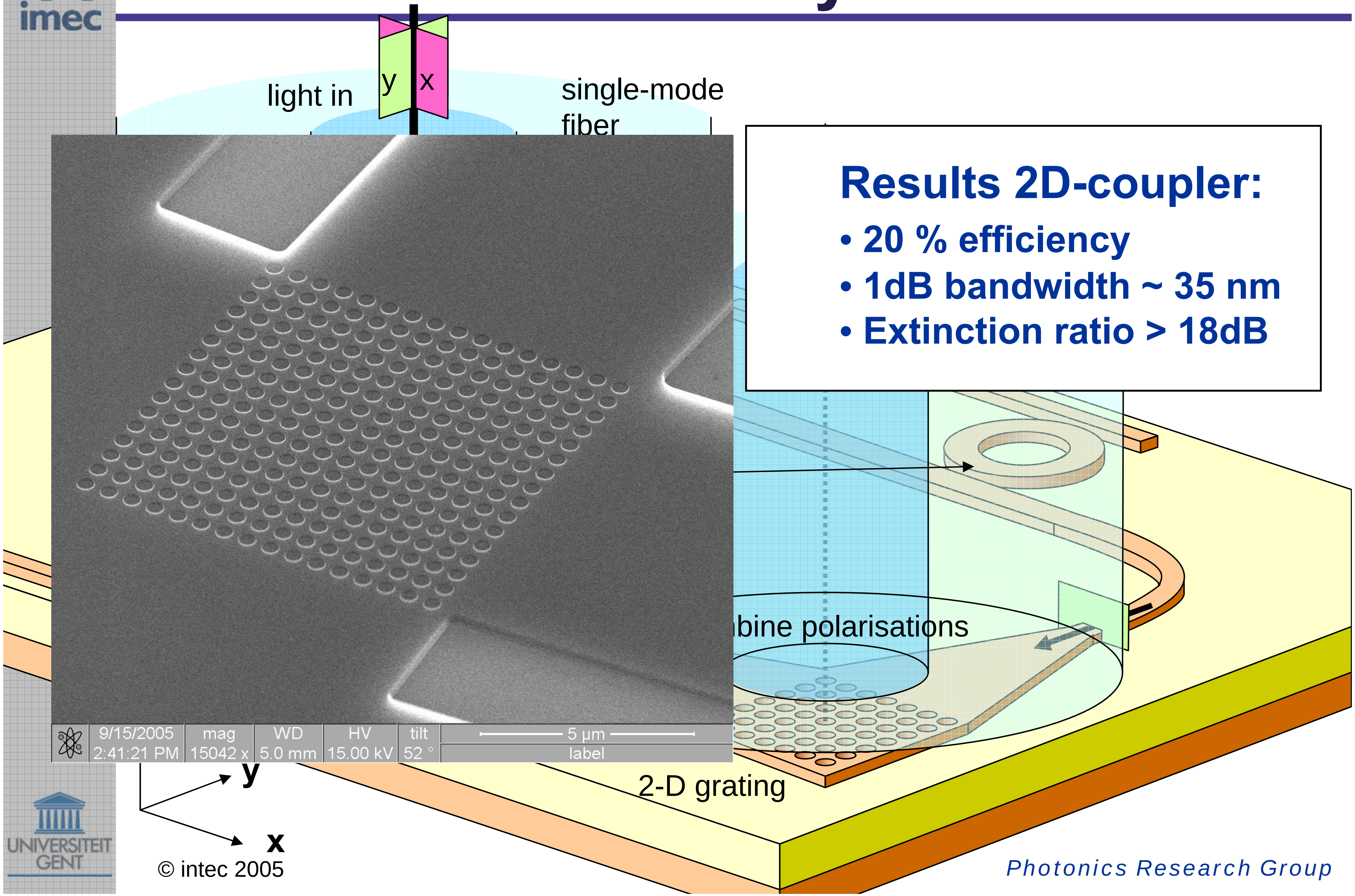


Taillaert et al. PTL 15(9) p. 1249 (2003)

Polarisation Diversity Circuit



Polarisation Diversity Circuit



Results 2D-coupler:

- 20 % efficiency
- 1dB bandwidth ~ 35 nm
- Extinction ratio > 18dB

Outline

Silicon Photonics: why and how?

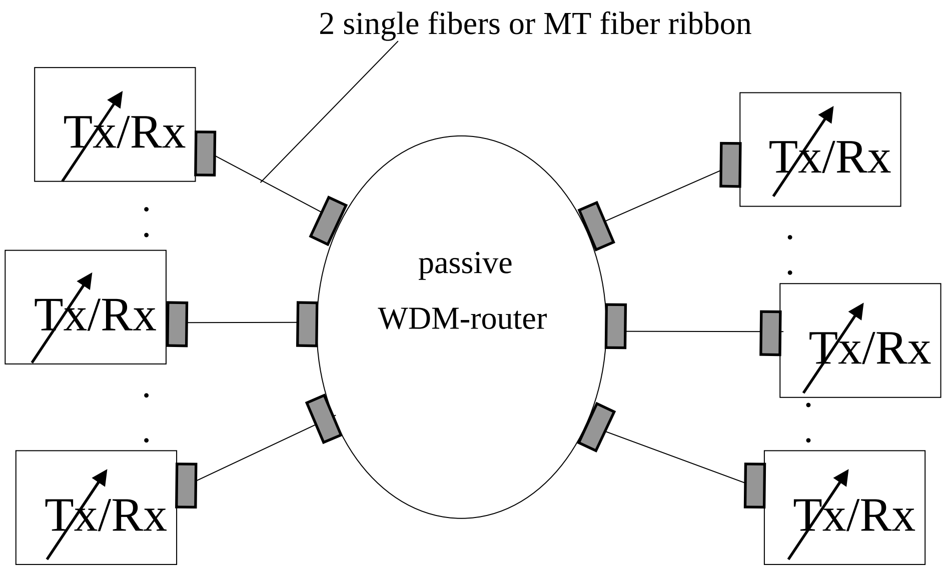
Passive wavelength routers in Silicon

Active photonic functions in Silicon

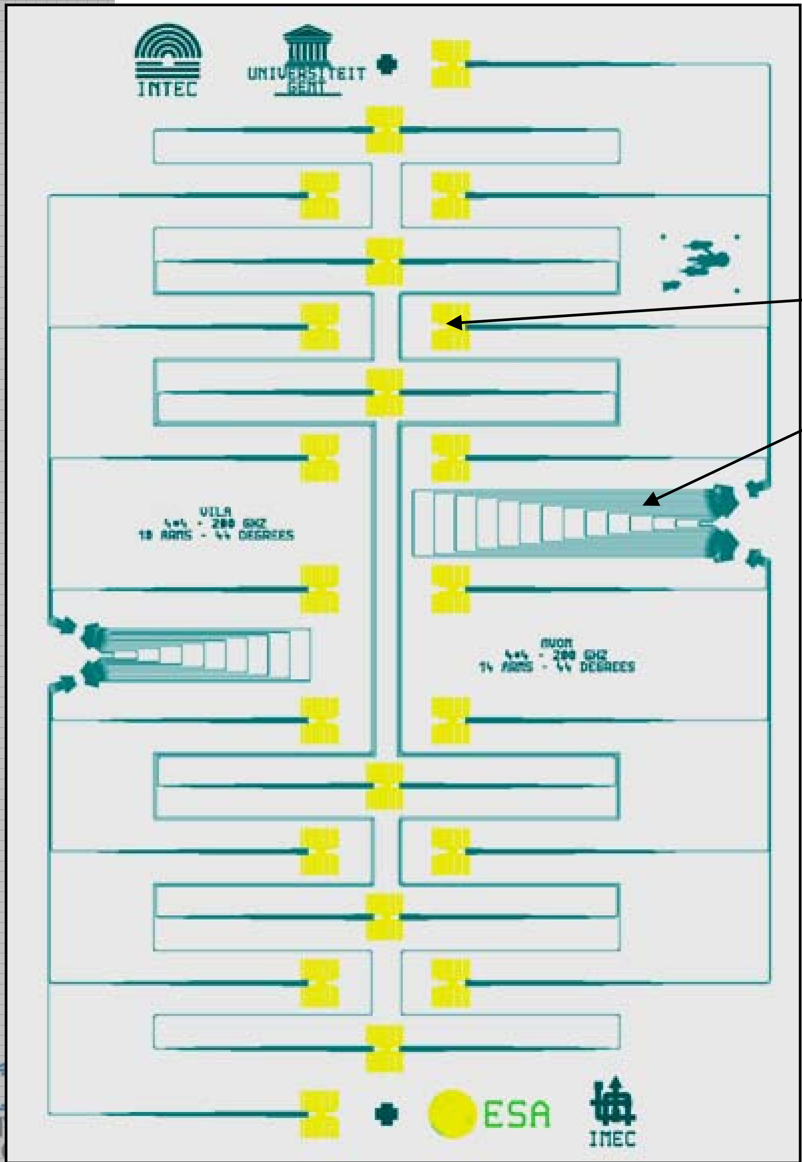
Silicon photonics: what for?

WDM switched optical backplane

- **routing functionality (w/o switches):** passive λ-based routing using tunable lasers
- Switching speed determined by tuning speed and by burst-mode receivers

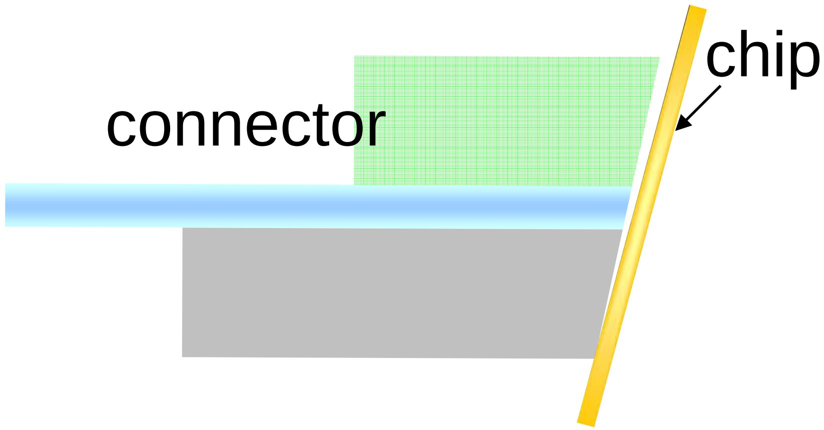


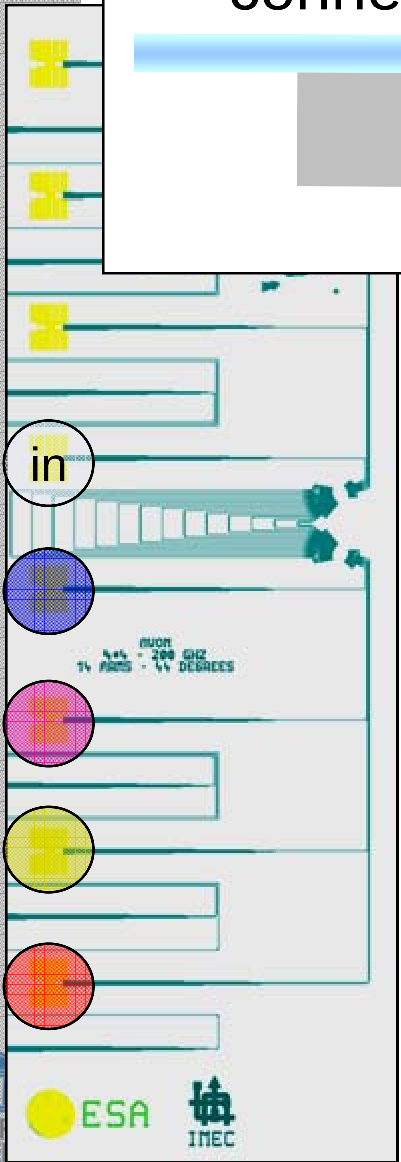
SOI wavelength router

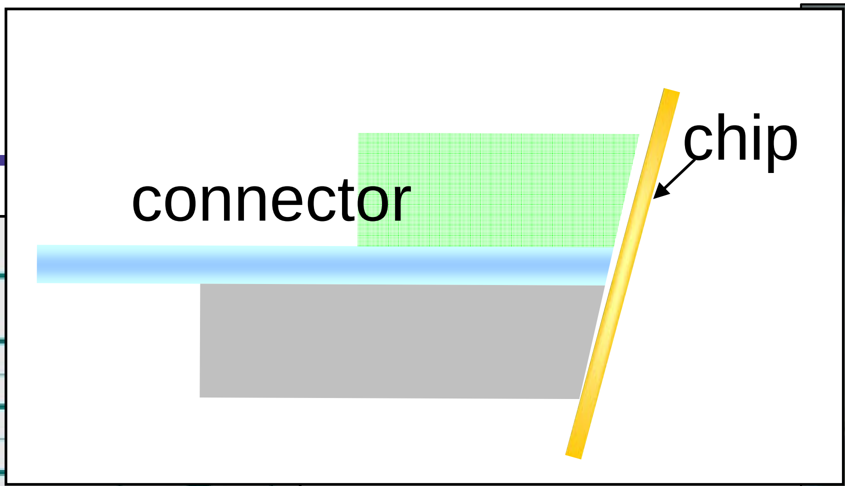


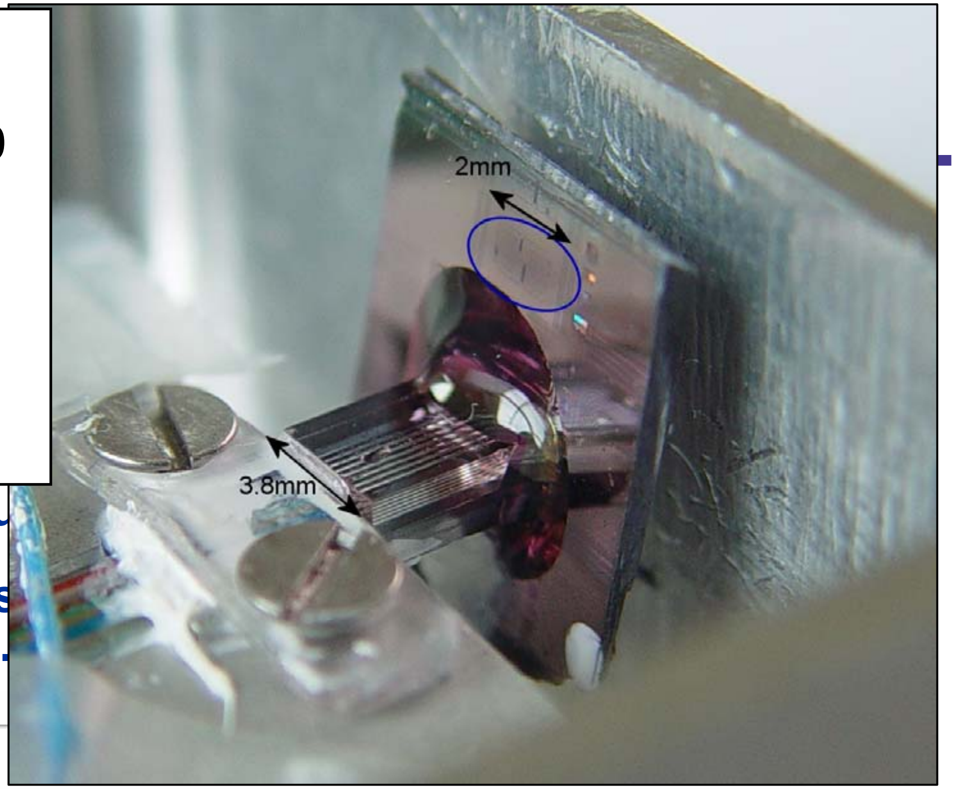
4 x 4 wavelength router

- Commercial connector with 8 fibers
- Vertical fiber couplers
- 4 x 4 AWG
- 200 GHz channel spacing

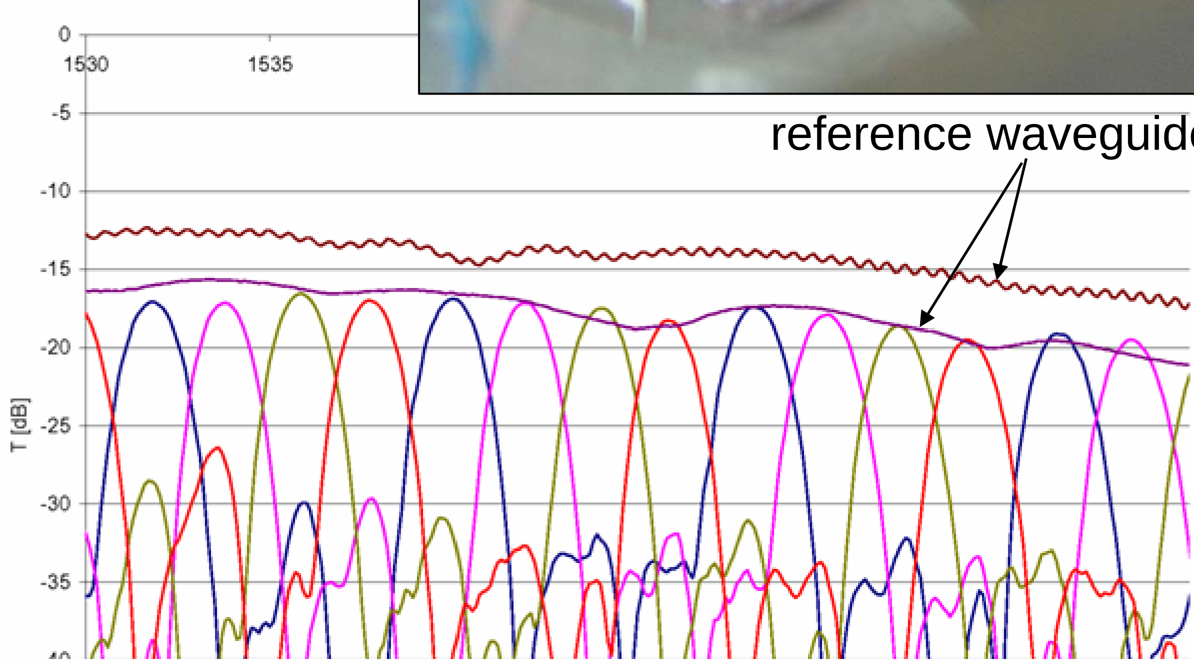








- **shallow star cou**
- **3.5dB device ins coupler), -12 to -**

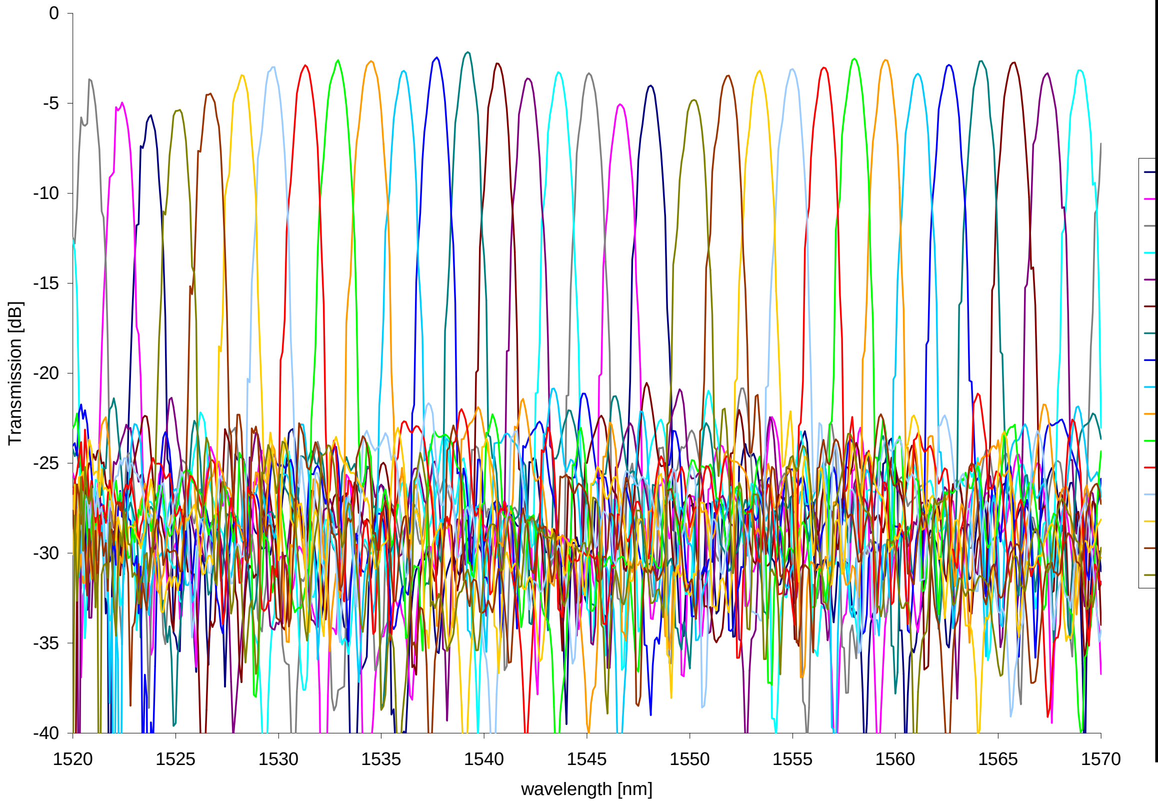


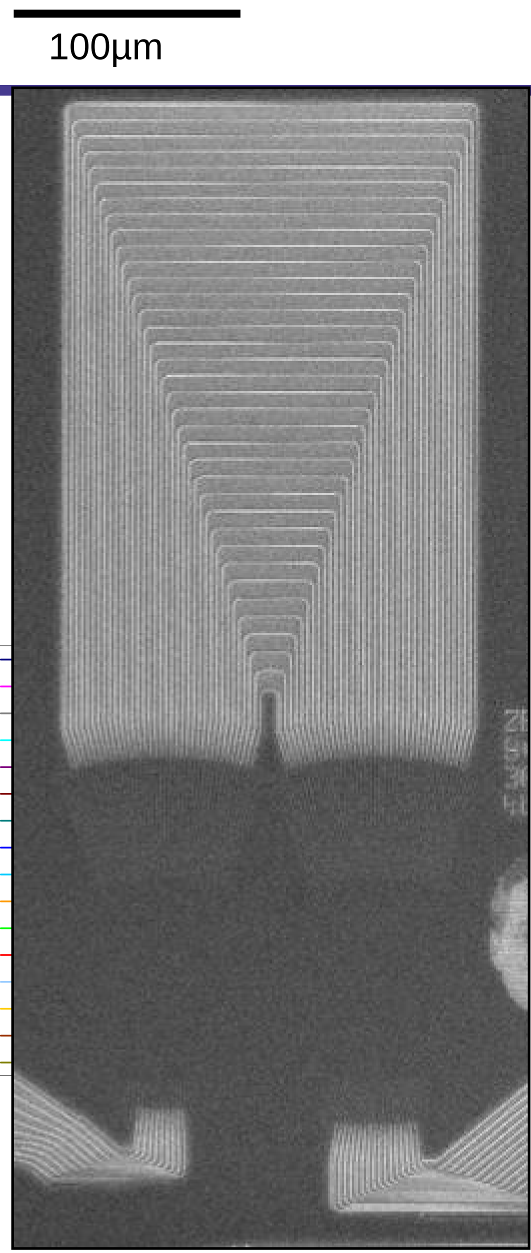
AWG

16-channel AWG, 200GHz

200µm x 500µm area

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





Outline

Silicon Photonics: why and how?

Passive wavelength routers in Silicon

Active photonic functions in Silicon

Silicon photonics: what for?

Active photonic functions

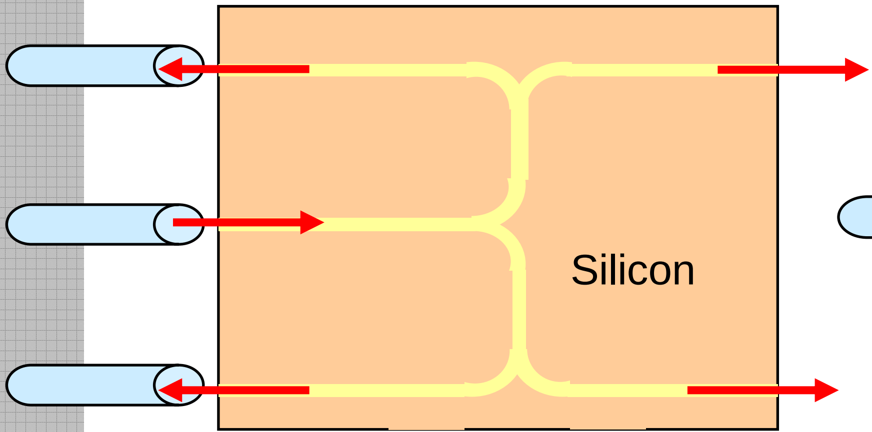
The options for modulation, switching, tuning at high speed:

- all Silicon approach
  - carrier density based optical effects + electric field induced carrier sweep away
  - All-optical approach using two-photon absorption
- Silicon + III-V-membrane integration
  - Using ultra-fast carrier lifetime in III-V
  - Also allowing light emission, gain, detection

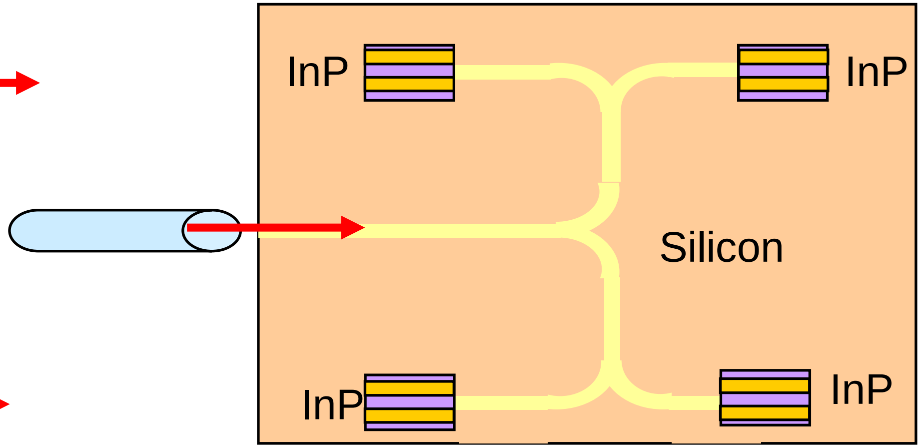
Heterogeneous integration

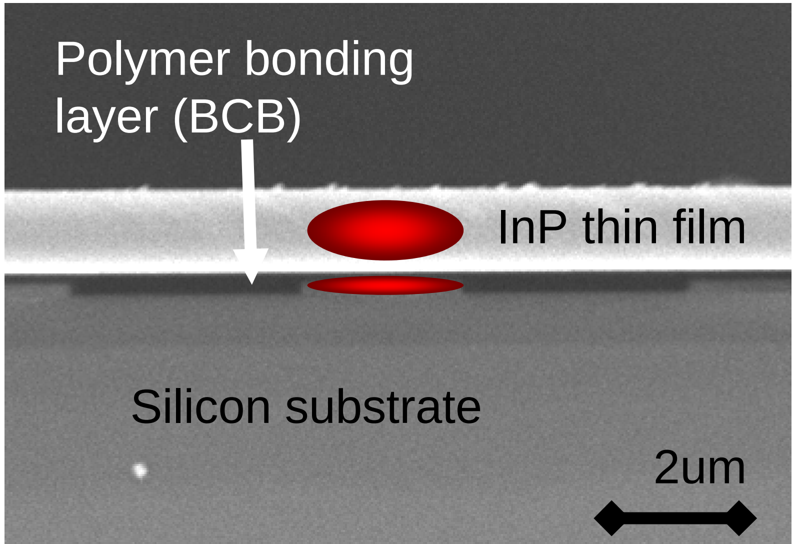
Silicon waveguide structure → *Heterogeneous circuit*

Passive only



Active + passive

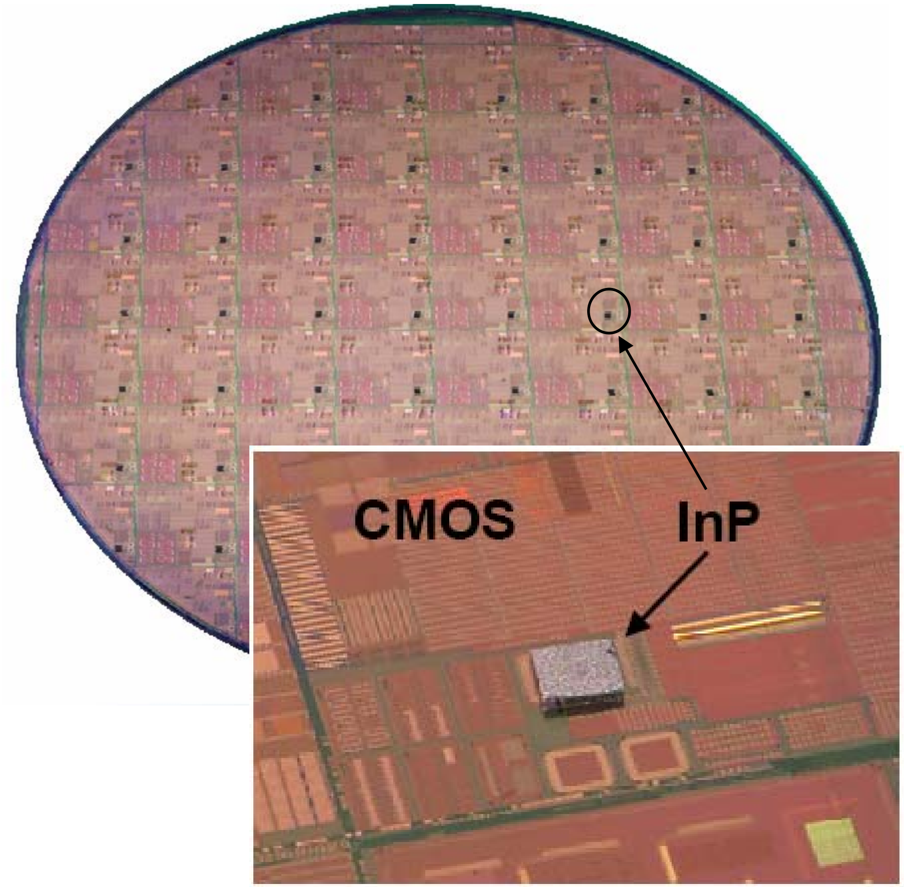




Die-to-wafer bonding

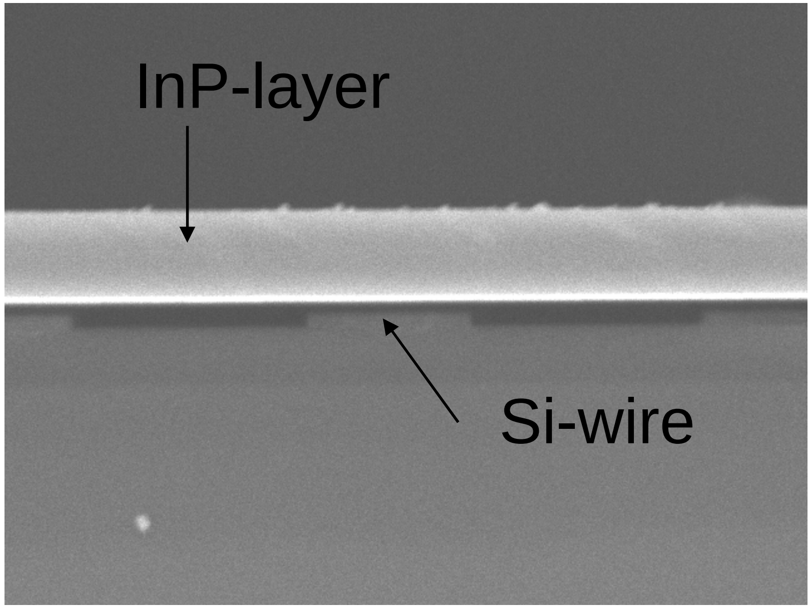
Molecular bonding

- InP on SOI-waveguides on CMOS demonstrated (LETI, TRACIT)



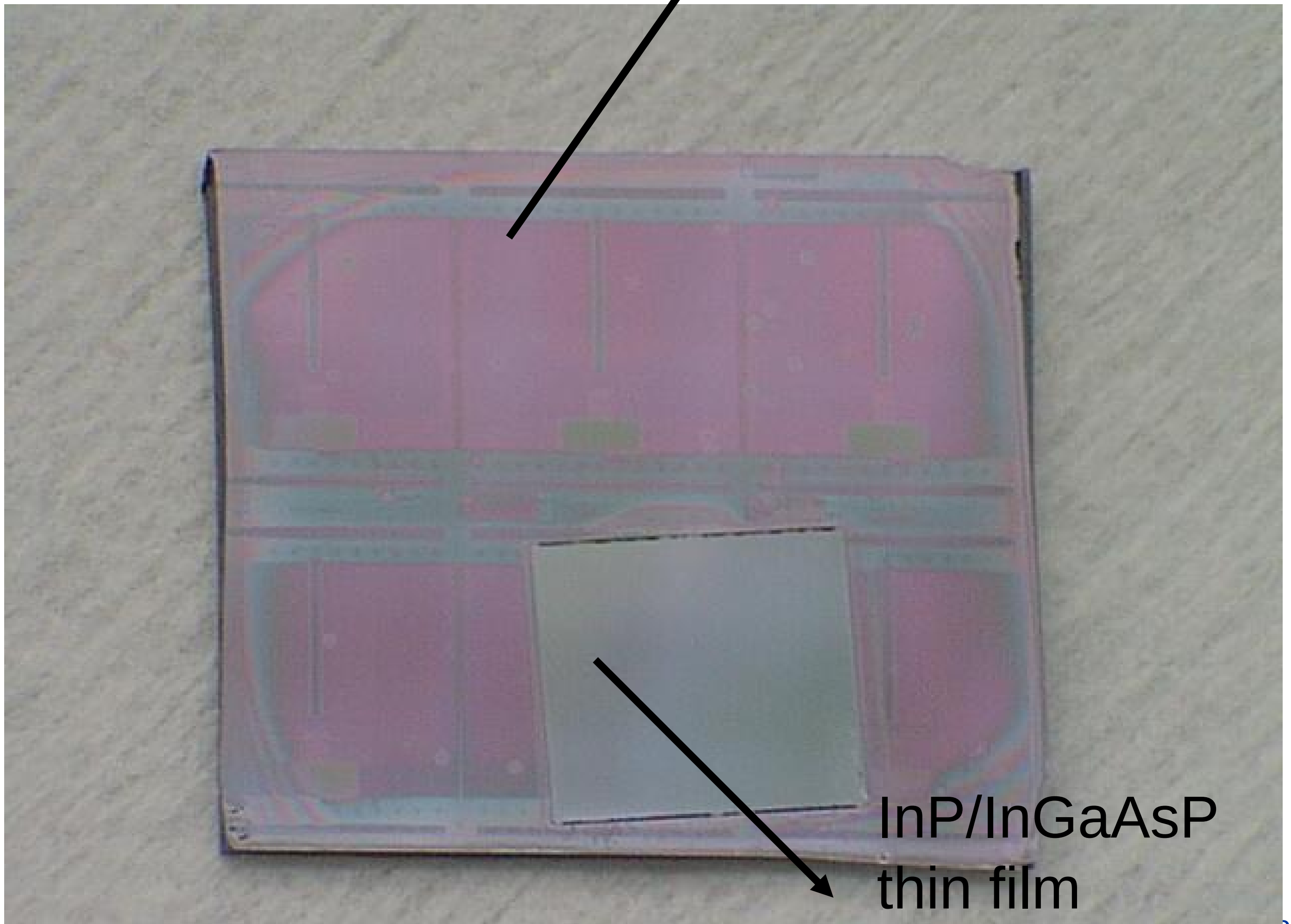
Polymer bonding

- Planarization and bonding in single step (IMEC)
- Ultra-thin bonding layers (sub 200nm demonstrated)

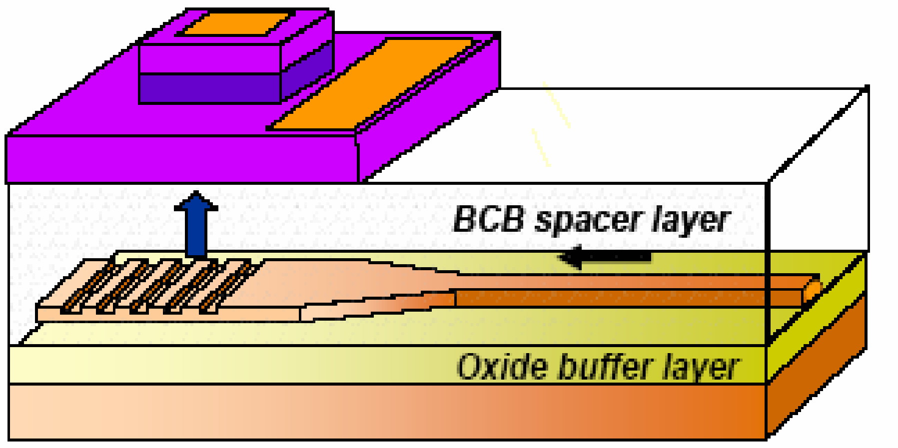


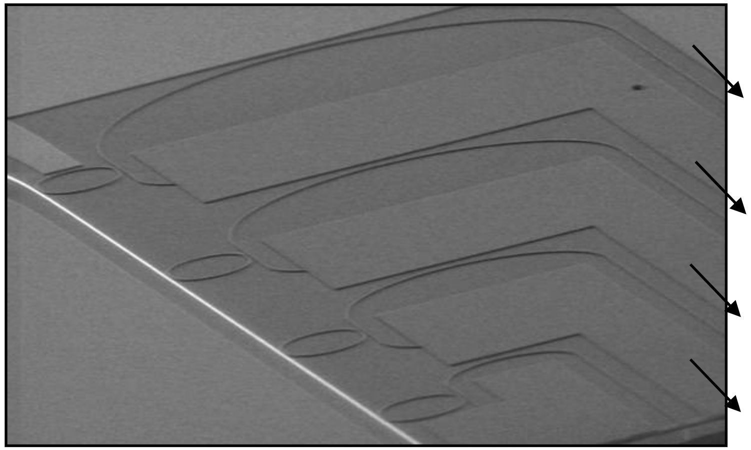
Die to wafer bonding technology

Good chemical resistance

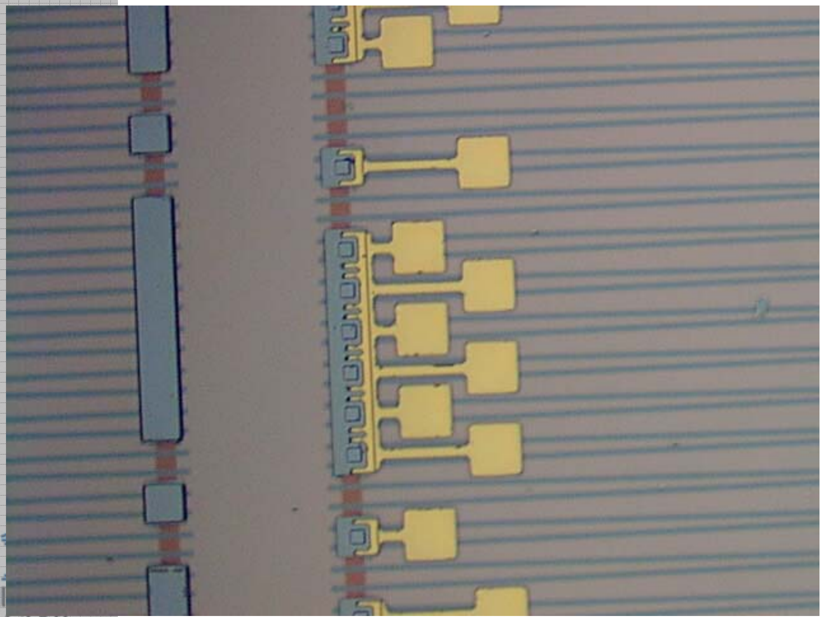


InGaAs Detectors on SOI

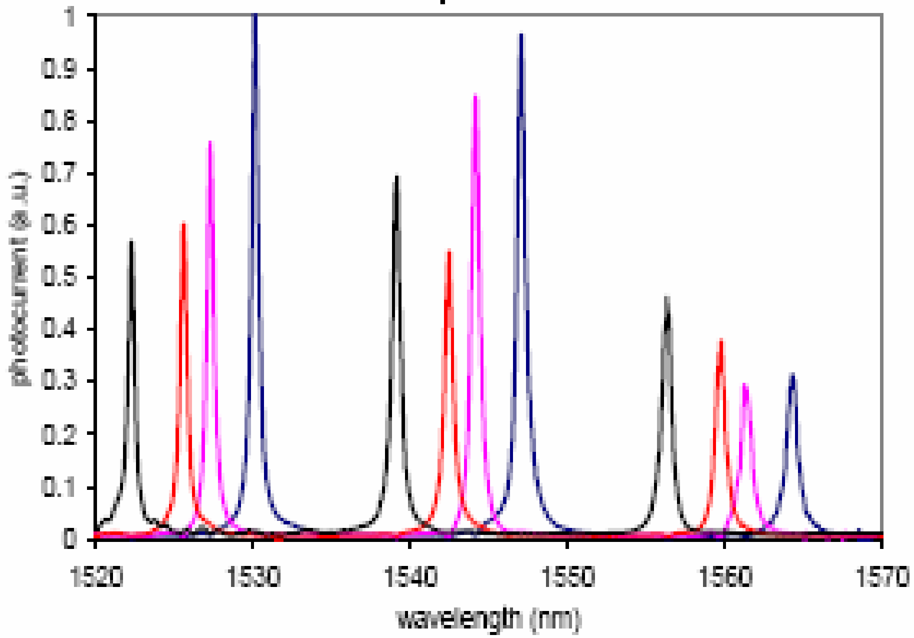




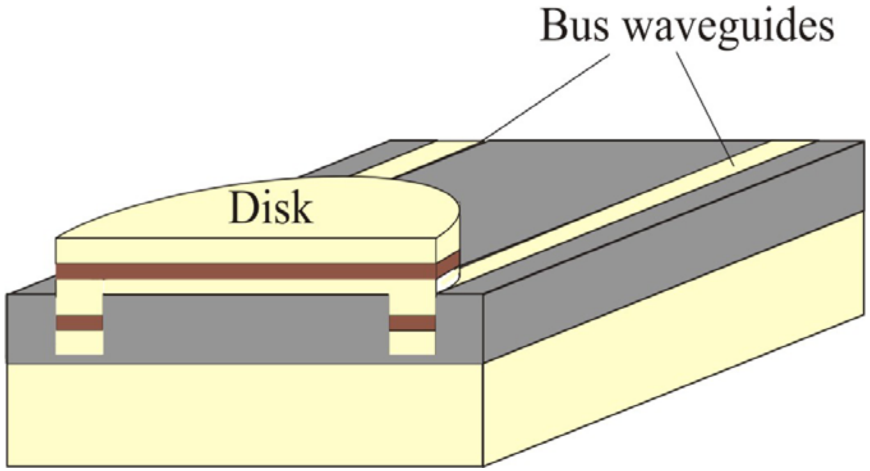
To detectors

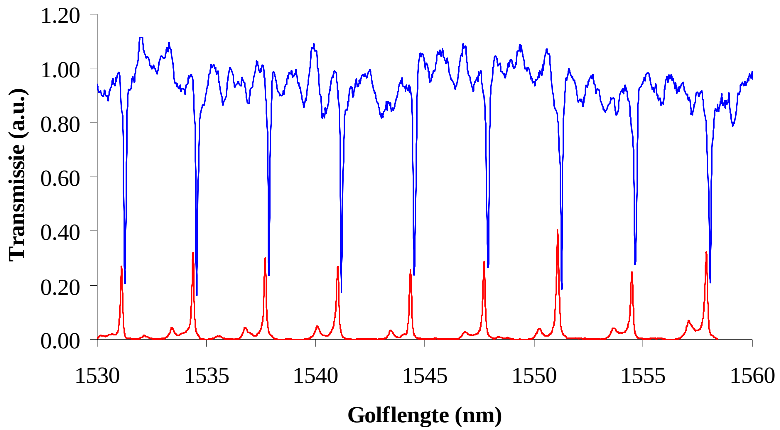


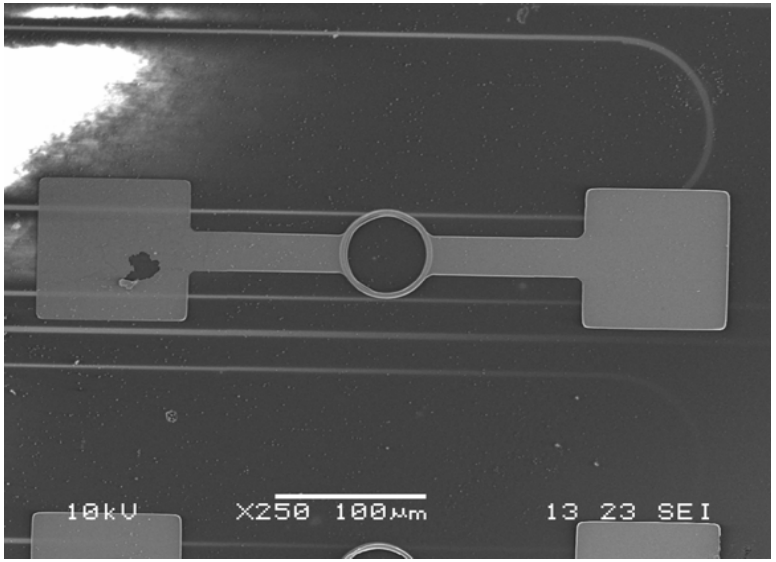
Measured response of 4 detectors



InP tunable ring resonators

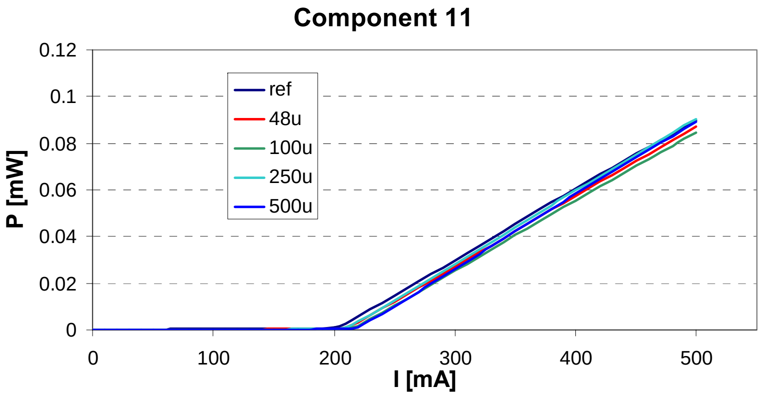


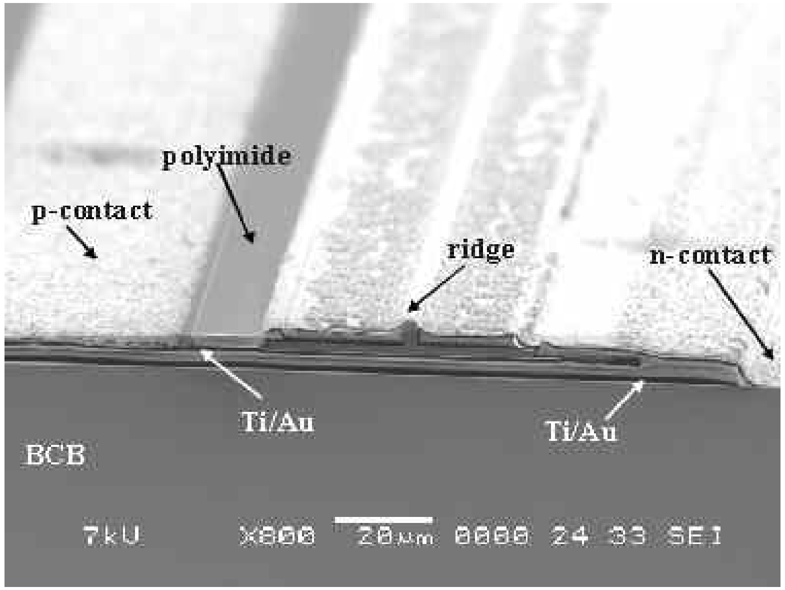




InP Fabry-Perot lasers

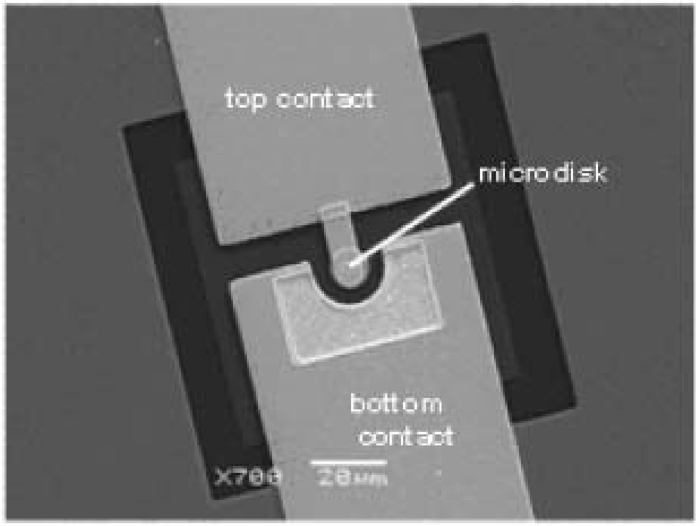
- Good functionality
- Damp-heat testing as proof of reliability of the BCB bonding process

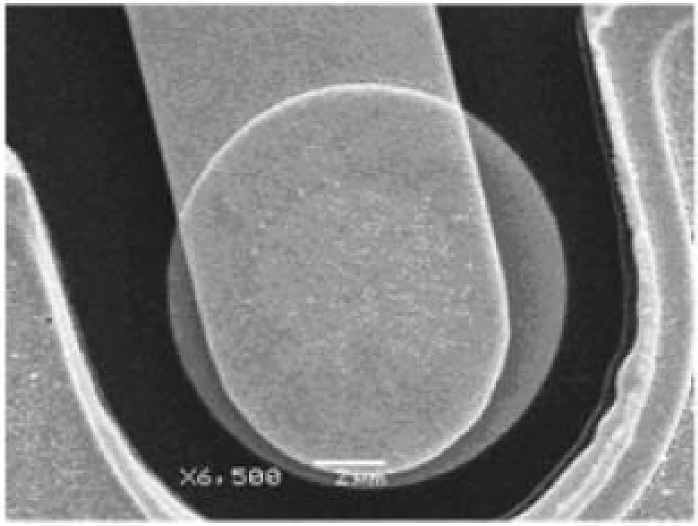


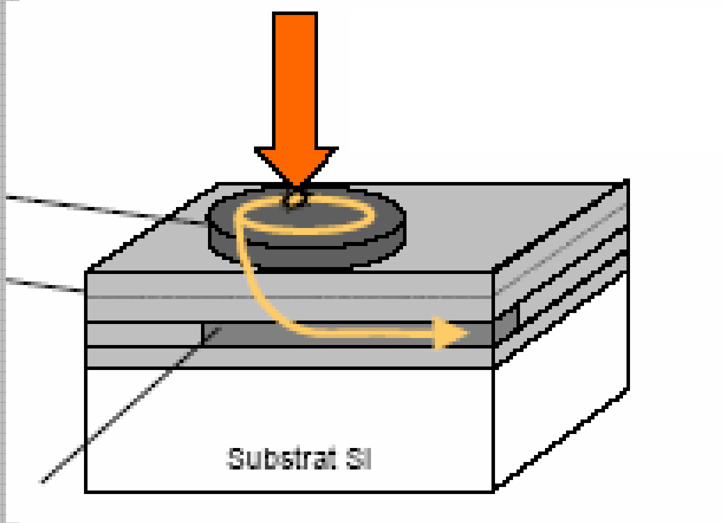


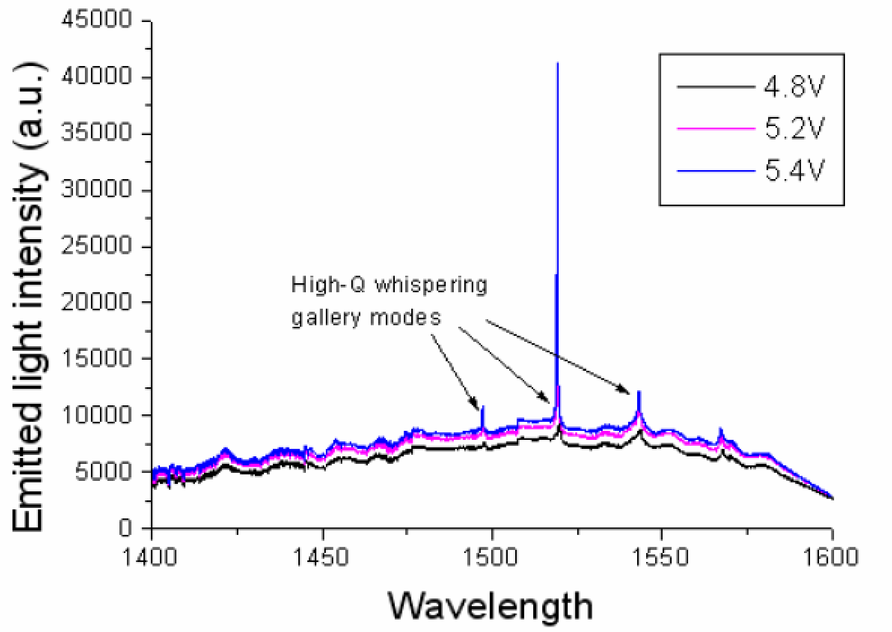
damp heat testing (85°C, 85% RH) for 48, 100, 250 and 500 hours

Electrically pumped InP microdisk laser

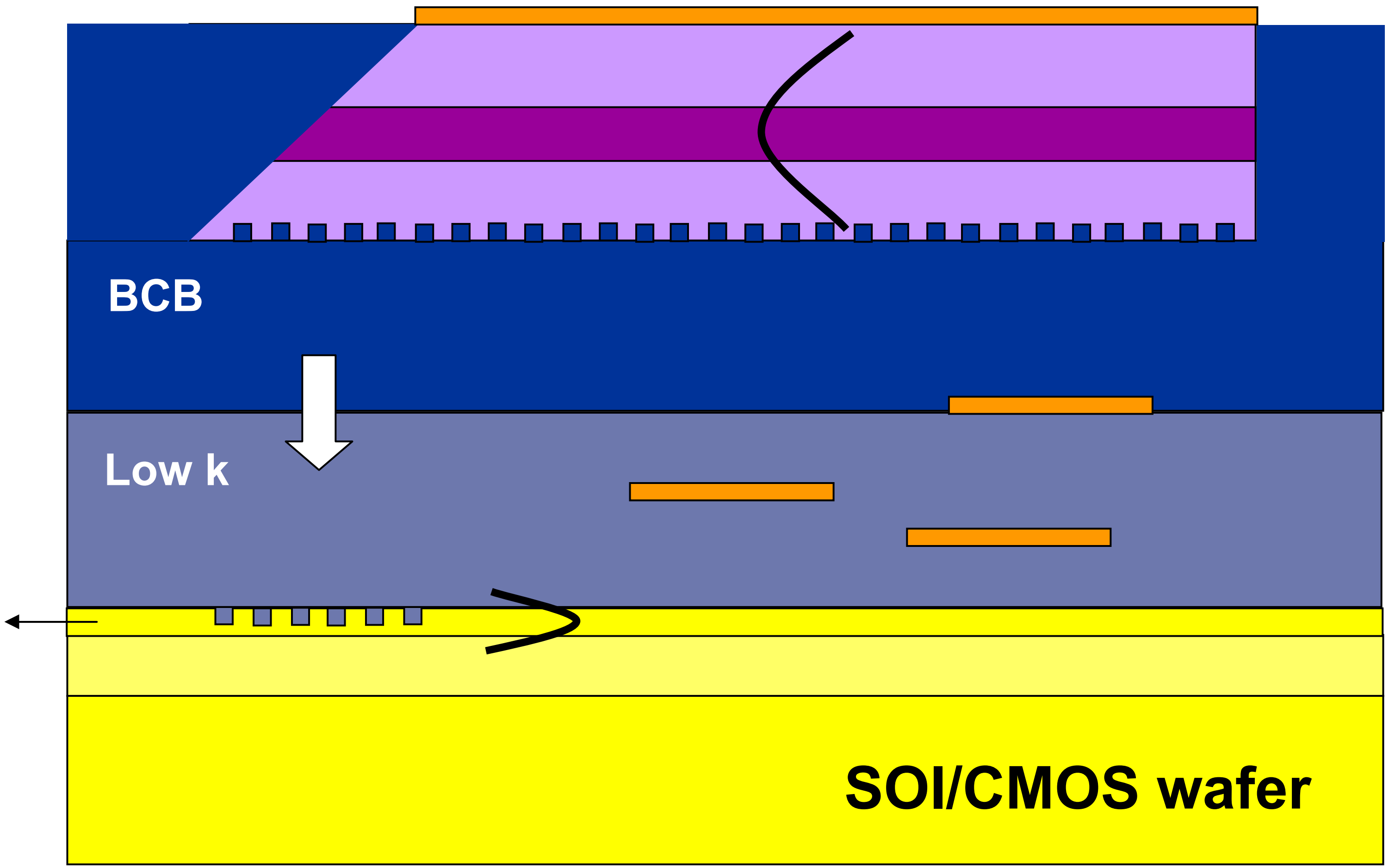








InP DFB laser diode coupled to SOI



grating coupler

Outline

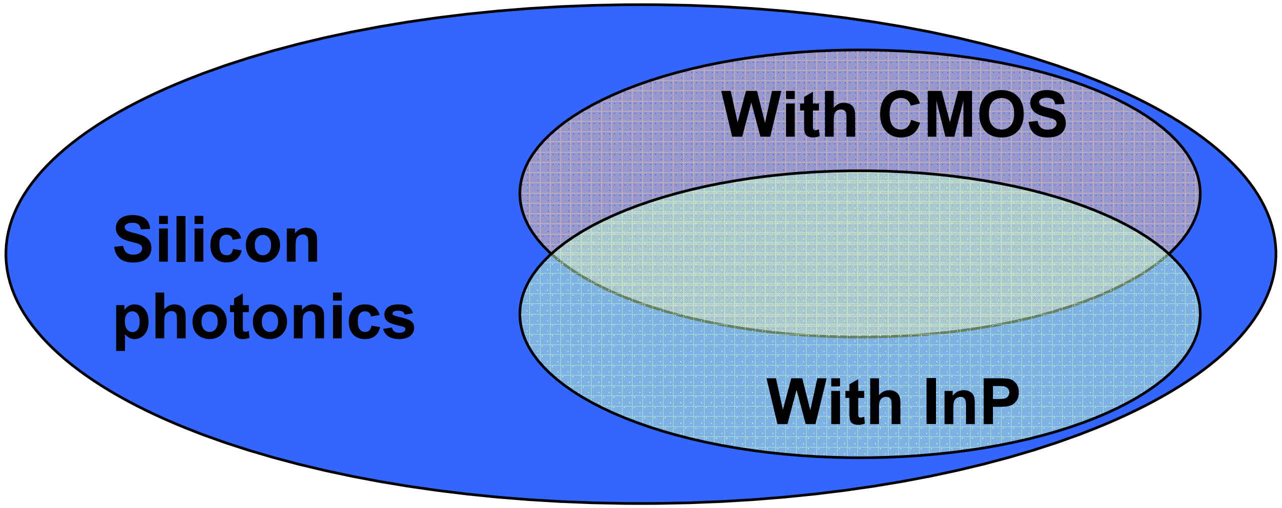
Silicon Photonics: why and how?

Passive wavelength routers in Silicon

Active photonic functions in Silicon

Silicon photonics: what for?

Silicon photonics: what for?



- WDM components
- switches for high speed backplanes
- single chip high speed low power transceivers
- on-chip optical interconnect
- sensors
- labs on a chip

Conclusion

Silicon photonics is a

generic technology

with a wide range of

high volume applications

for which the

industrial technology base

largely exists

today.