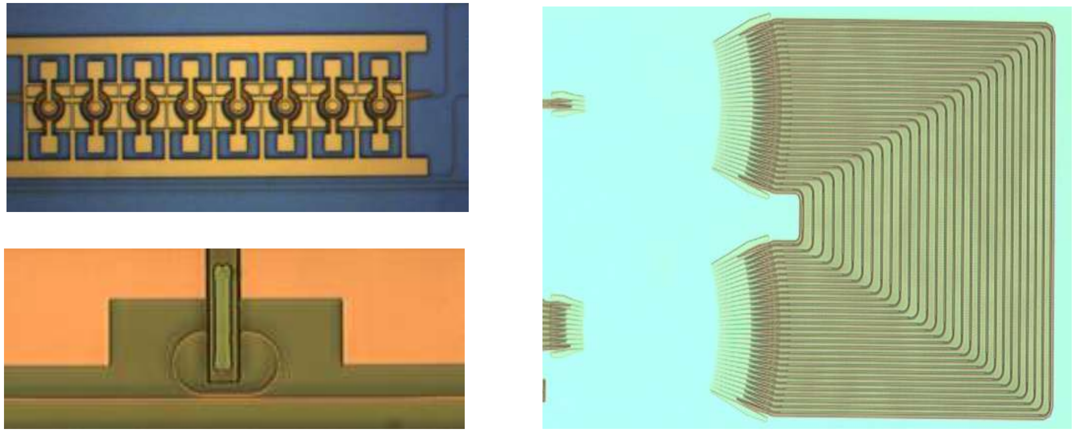
A silicon nanophotonic platform for optical interconnects

D. Van Thourhout

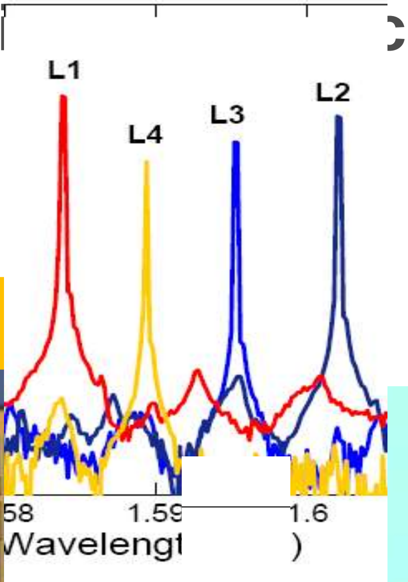
Photonics Research Group, Ghent University/ IMEC

Dec. 9, 2010

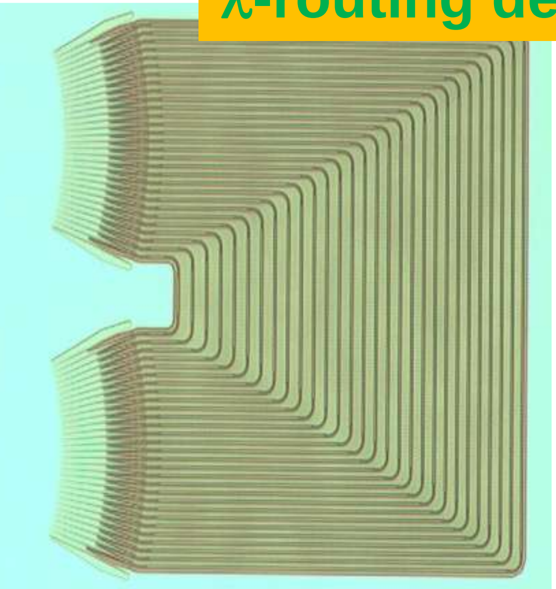


Nanophotonic Devi cal Networks-On-Chip

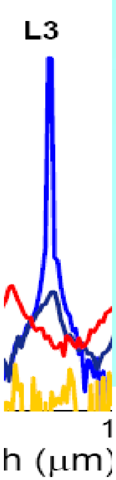
multi-λ microdisk laser



λ-routing devices



λ-selective detectors



The Photonics Research Group

Research group of Ghent University

- associated with IMEC

Staff

- 6 Professors:
  - R. Baets, D. Van Thourhout, P. Bienstman, G. Morthier, G. Roelkens, W. Bogaerts.
- 8 postdocs
- 30+ PhD students

Device research

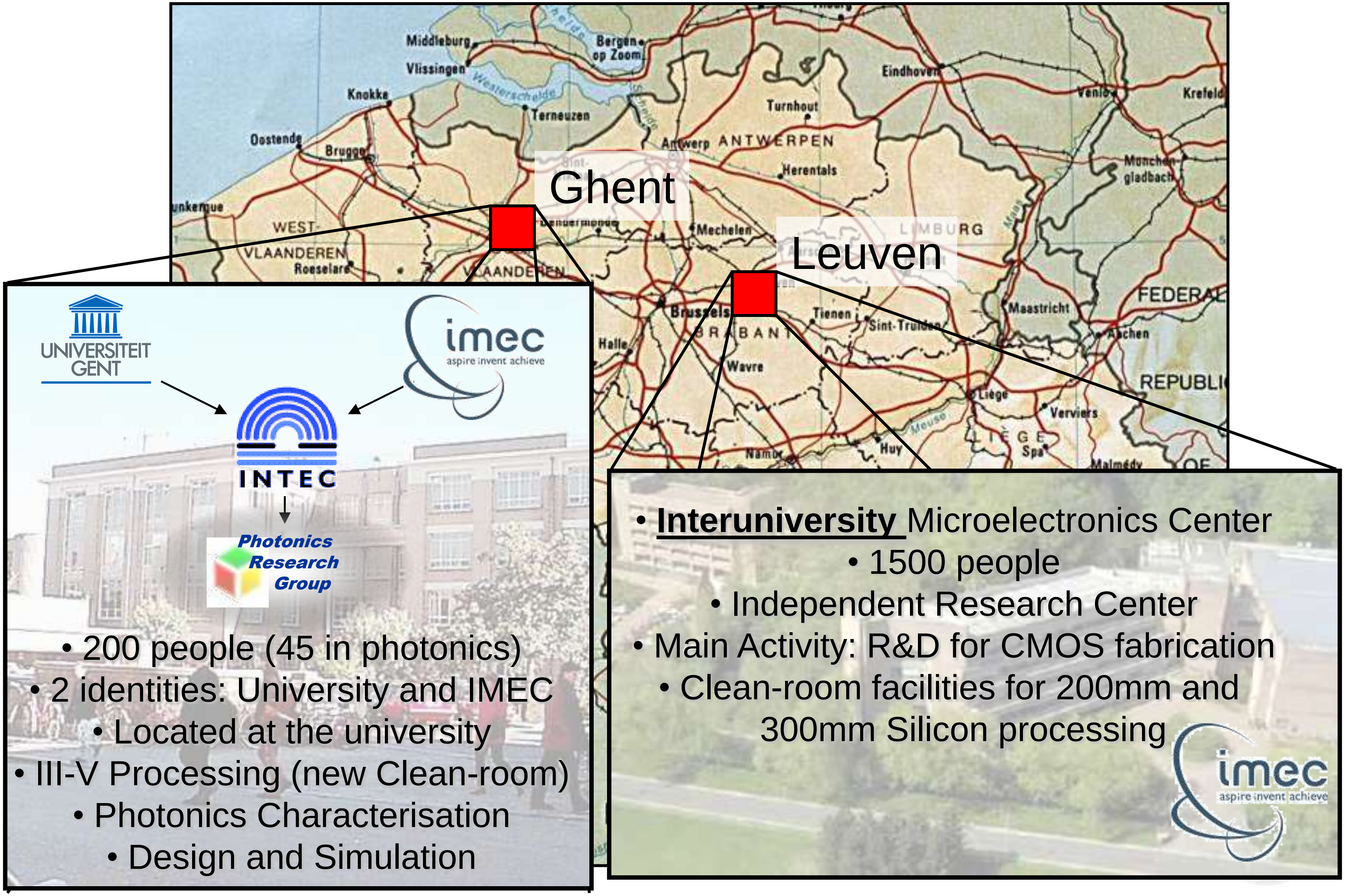
- Silicon photonics
- Putting stuff on photonics

Towards applications

- Telecom, datacom, interconnect
- Sensing (bio- + environmental)

http://photonics.intec.ugent.be

IMEC - INTEC



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INTEC

Photonics Research Group

- 200 people (45 in photonics)
- 2 identities: University and IMEC
- Located at the university
- III-V Processing (new Clean-room)
- Photonics Characterisation
- Design and Simulation

- **Interuniversity** Microelectronics Center
- 1500 people
- Independent Research Center
- Main Activity: R&D for CMOS fabrication
- Clean-room facilities for 200mm and 300mm Silicon processing

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Rationale

2018-2022 time frame:

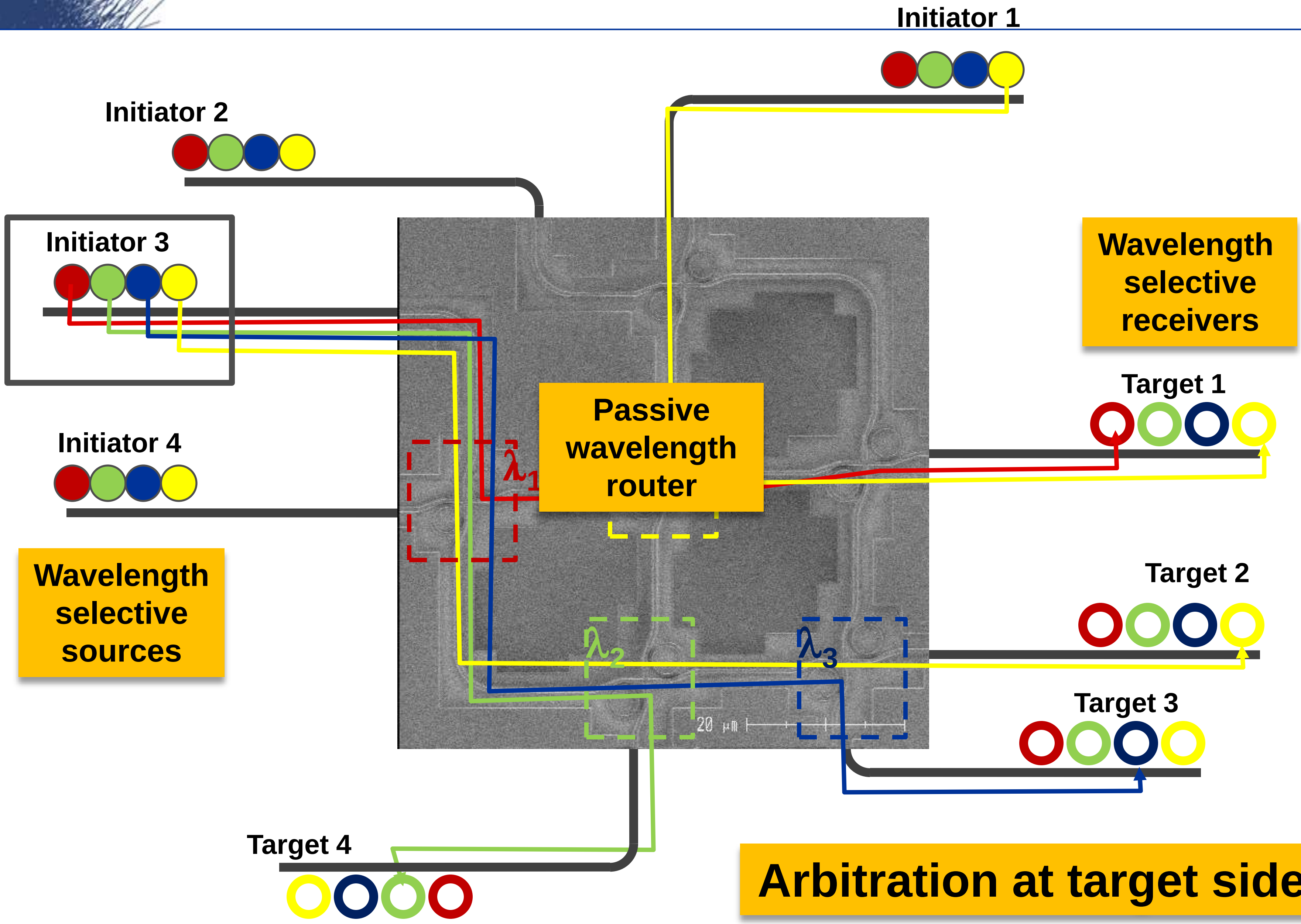
- Current electrical interconnects no longer capable of handling required data streams (on-chip and chip-to-chip)
- Need fundamental new solutions
  - New type of electrical interconnects ?
  - Optical interconnects ?
- Very [illegible] conditions
  - 1pJ/bit (=1mW/Ghz) often quoted
  - Several 10 Tb/s on-chip
  - Other people quote 0.1pJ/bit or even 0.01pJ/bit !!
  - Fabrication using waferscale methods
  - Low cost packaging

See talk prof. Miller ….

Rationale

EU-project WADIMOS

- Wavelength Division Multiplexing on CMOS
- Partners
  - IMEC, CEA-LETI, STMicroelectronics
  - INL, TRENTO, MAPPER
- Time frame : Jan. 2008- Jun. 2011
- Our goal:
  - Develop technology platform for realizing photonic layer on CMOS
  - Using wavelength routing for steering signals



Wavelength selective sources

Passive wavelength router

Wavelength selective receivers

Arbitration at target side !

Rationale

Wavelength routed network

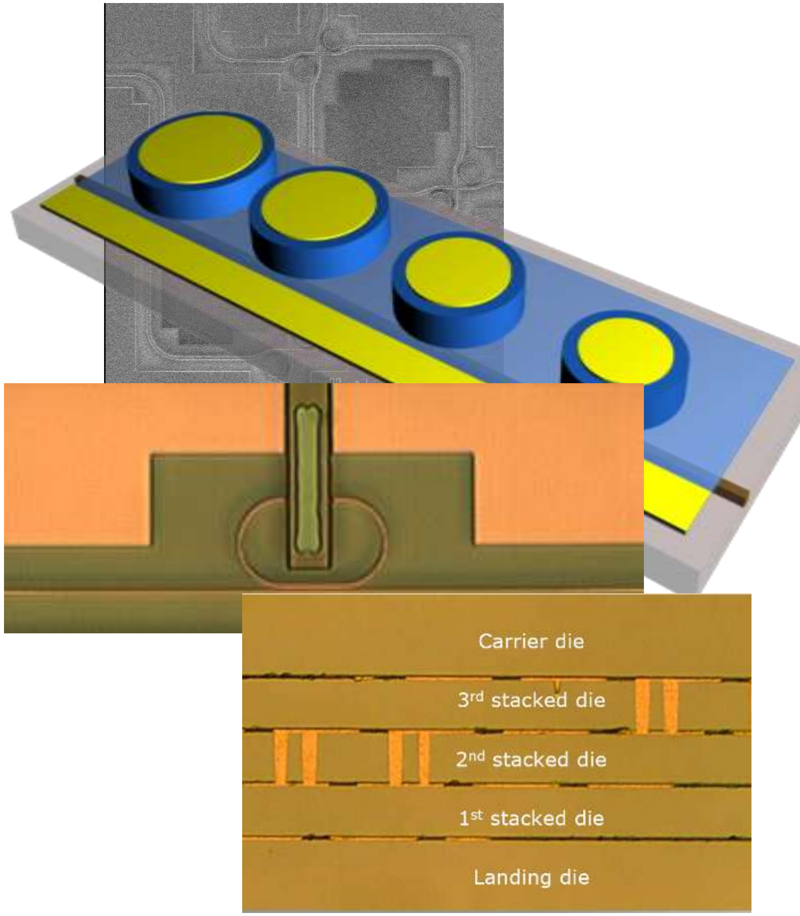
- Scalable by increasing number of wavelengths
- Using wavelength conversion to connect sub-domains

Need

- Passive routing circuitry
- Multi-wavelength lasers
- Wavelength selective detectors
- Integration with electronics

Relevant specifications

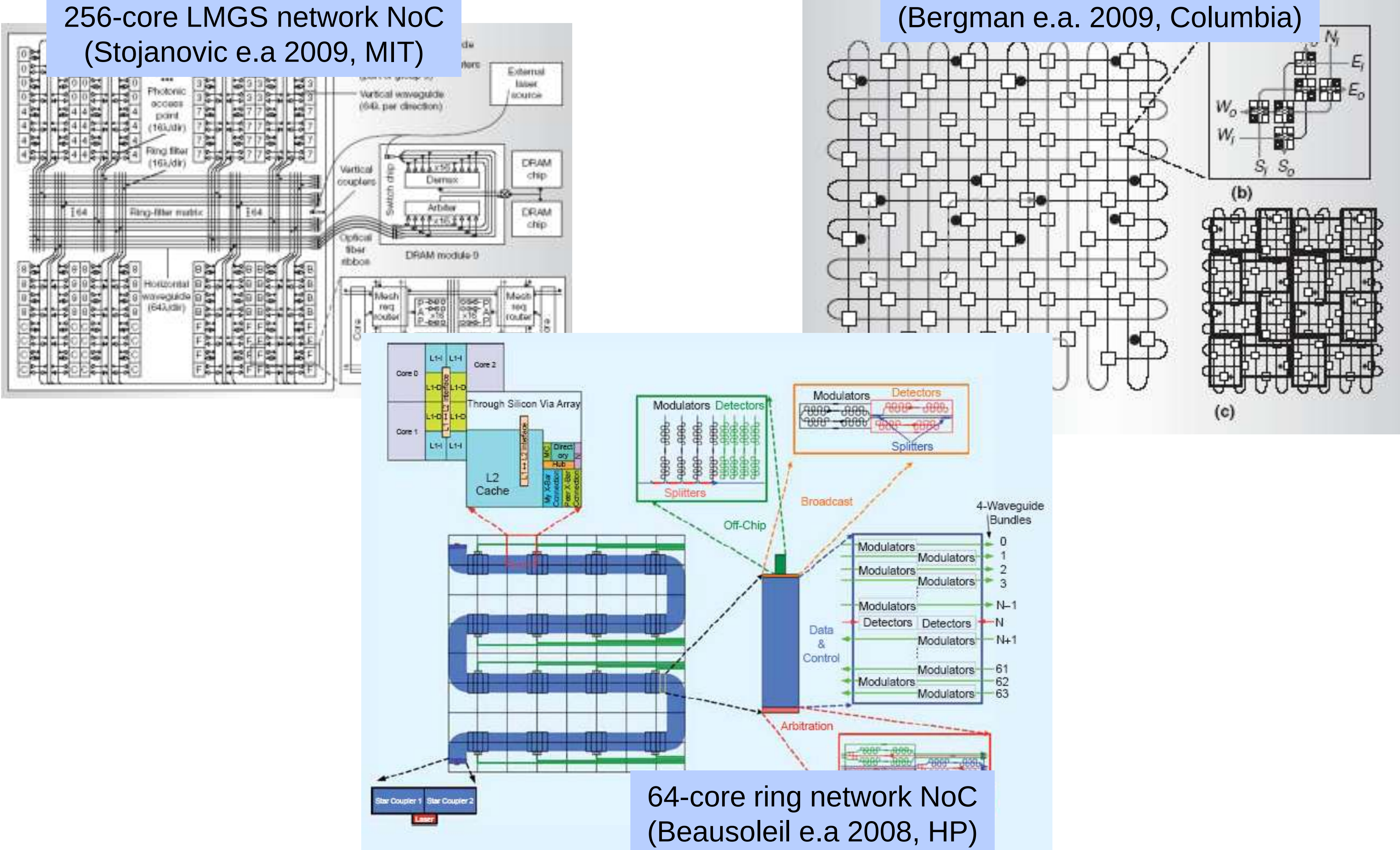
- Waferscale fabrication!
- Power consumption, size, speed



See talk prof. Miller ….

Rationale

Alternative routing schemes



256-core LMGS network NoC
(Stojanovic e.a 2009, MIT)

16-core torus NoC
(Bergman e.a. 2009, Columbia)

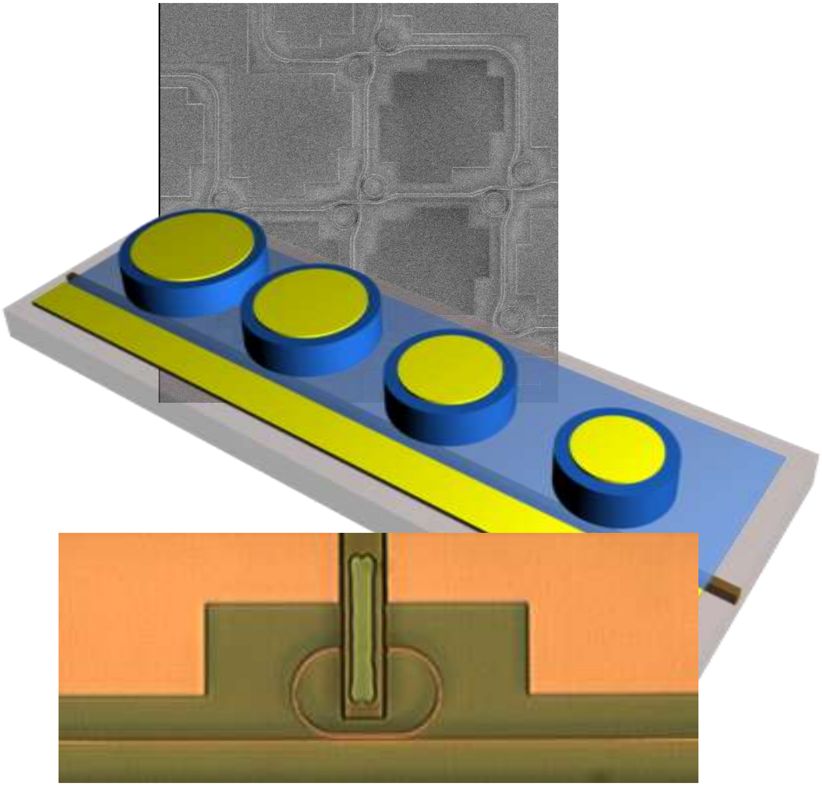
64-core ring network NoC
(Beausoleil e.a 2008, HP)

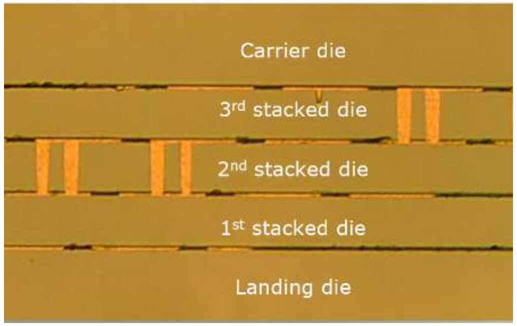
Outline

Outline

- Passive routing circuitry
- Multi-wavelength lasers
- Wavelength selective detectors
- Integration with electronics

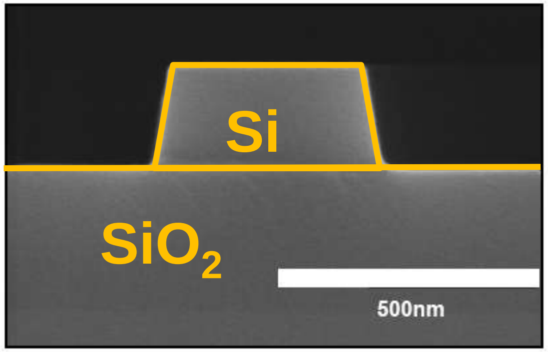
- Some other applications …
- How to get access to technology

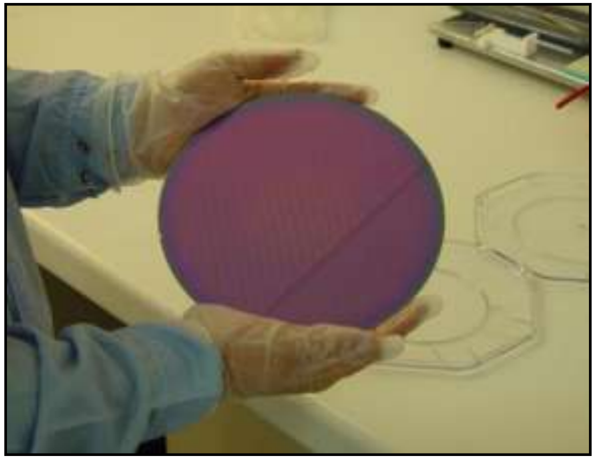


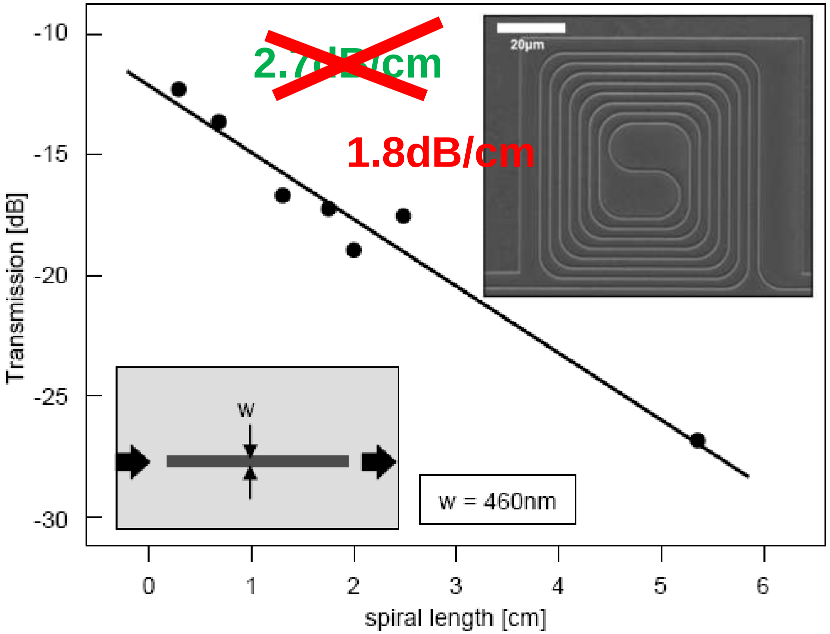


Silicon waveguide platform

- Transparent at telecom wavelengths (1.3 µm, 1.55 µm)
- High refractive index contrast ➔ ultra-compact circuits
- “Compatible” with CMOS-processing
  - Highest quality processes
  - High yield, high repeatability
  - Leverage of existing infrastructure
  - Leverage of existing processes
- Integration with electronics`







Why Silicon ?

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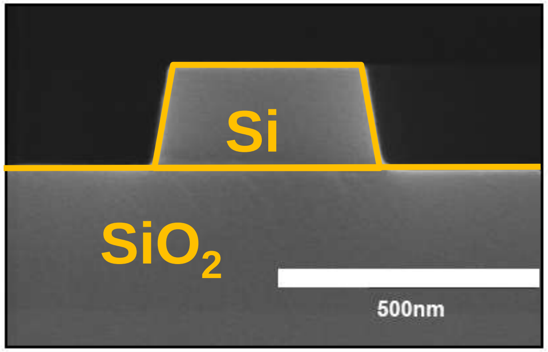
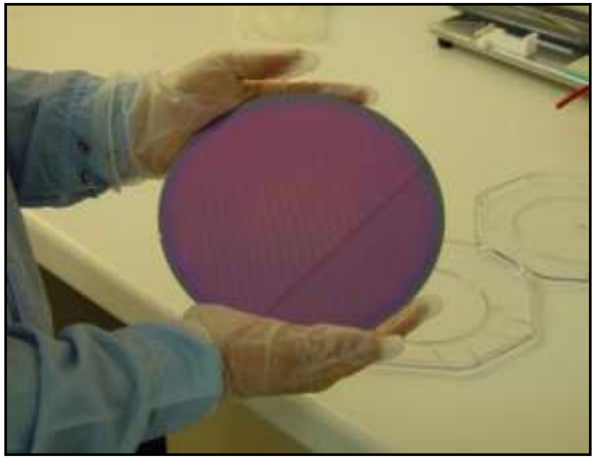
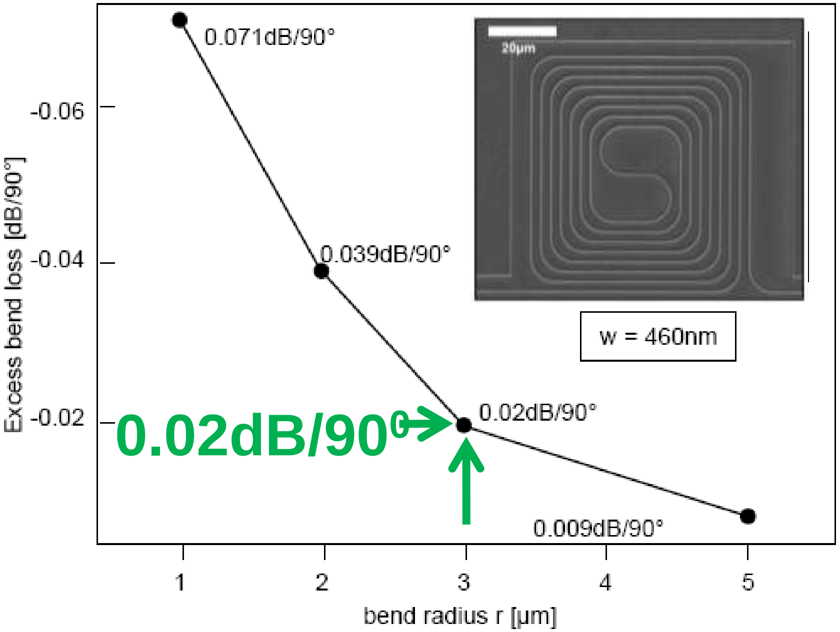
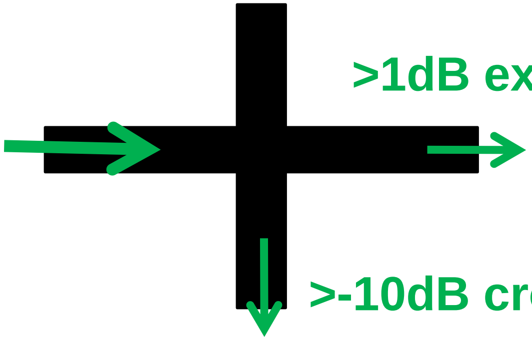






Crossings

Standard Crossing

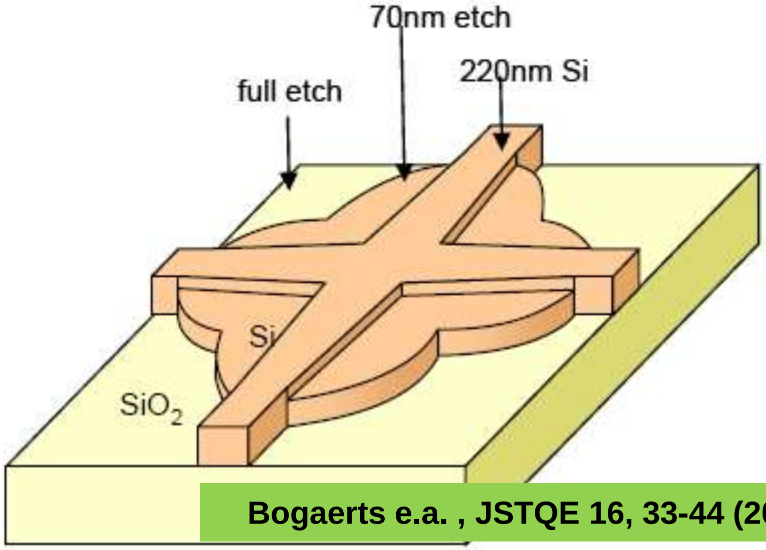


>1dB excess loss

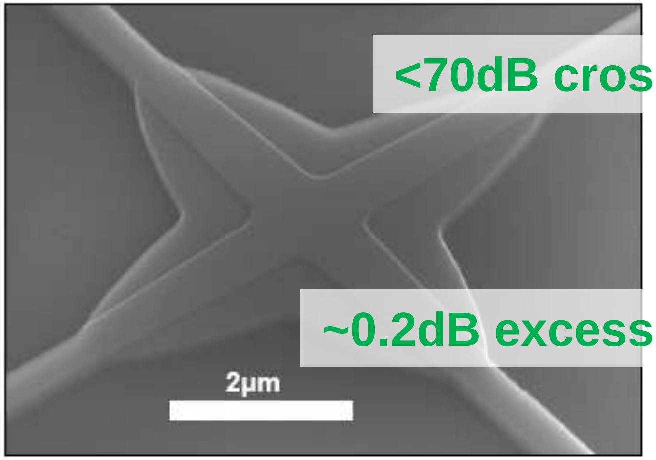
>-10dB crosstalk

Not practical !

Improved version

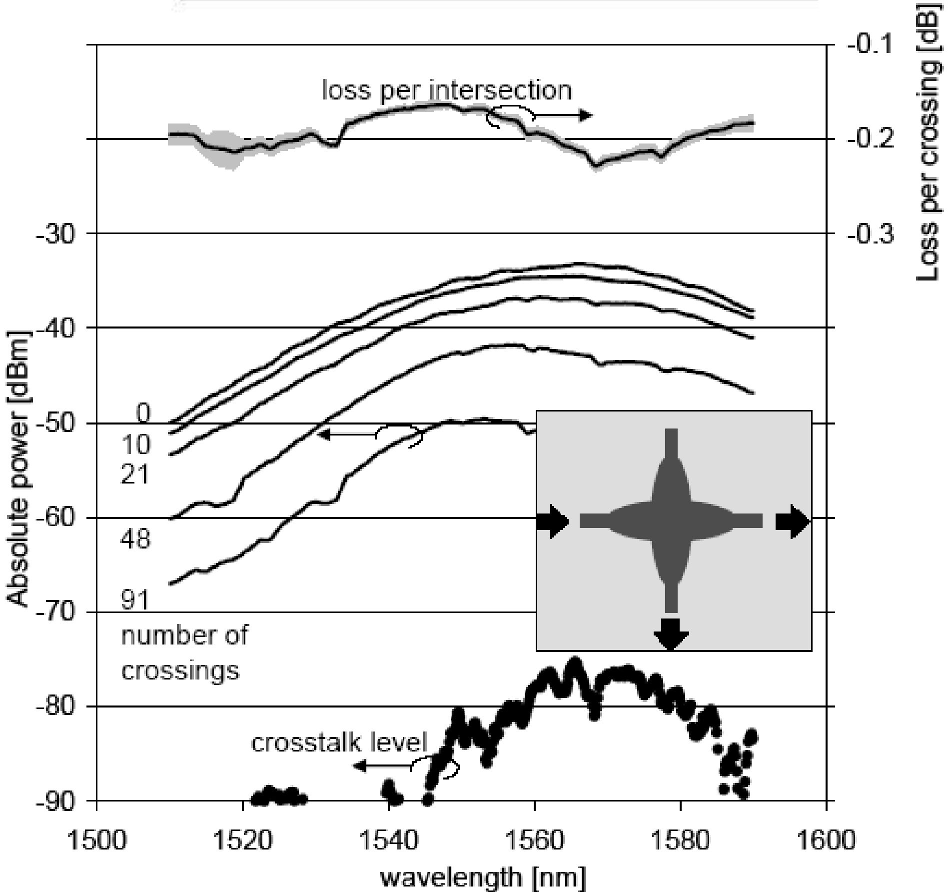


Bogaerts e.a. , JSTQE 16, 33-44 (2010)



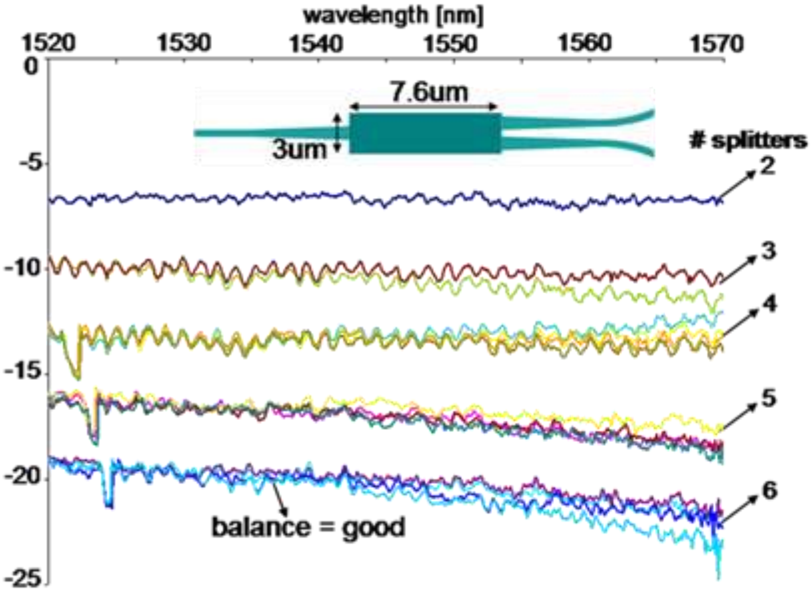
<70dB crosstalk

~0.2dB excess loss



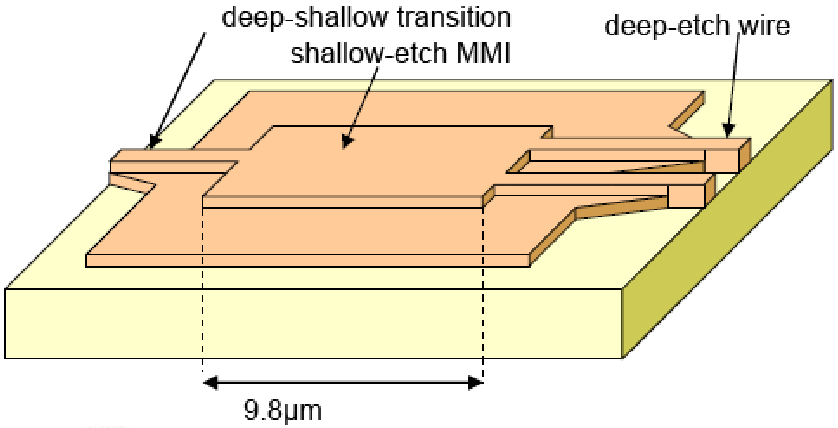
Passive guiding structures

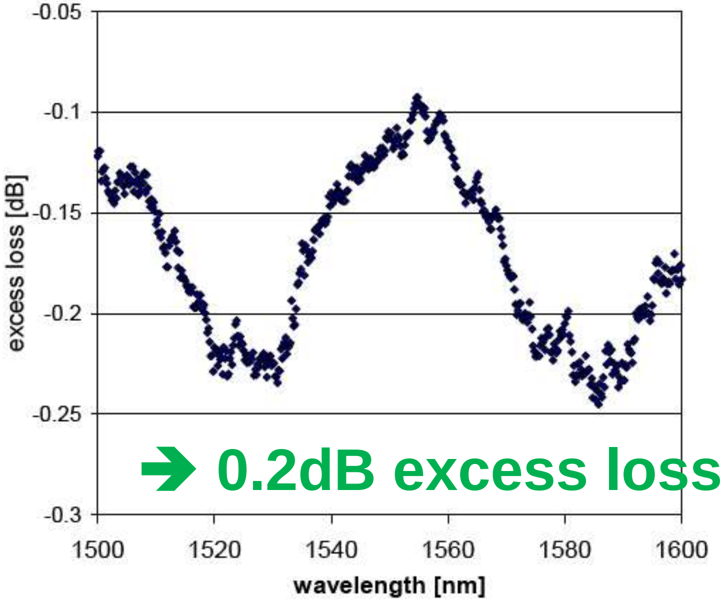
Standard MMI splitter



➔ 0.3dB excess loss

Improved version



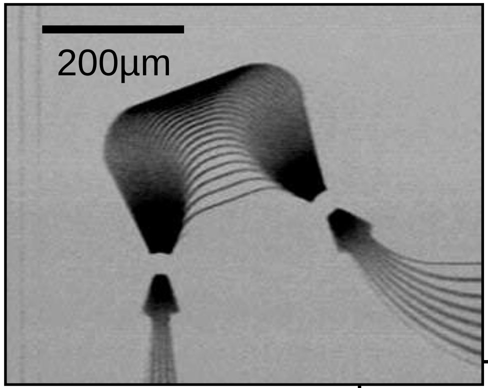


➔ 0.2dB excess loss

Bogaerts e.a. , JSTQE 16, 33-44 (2010)

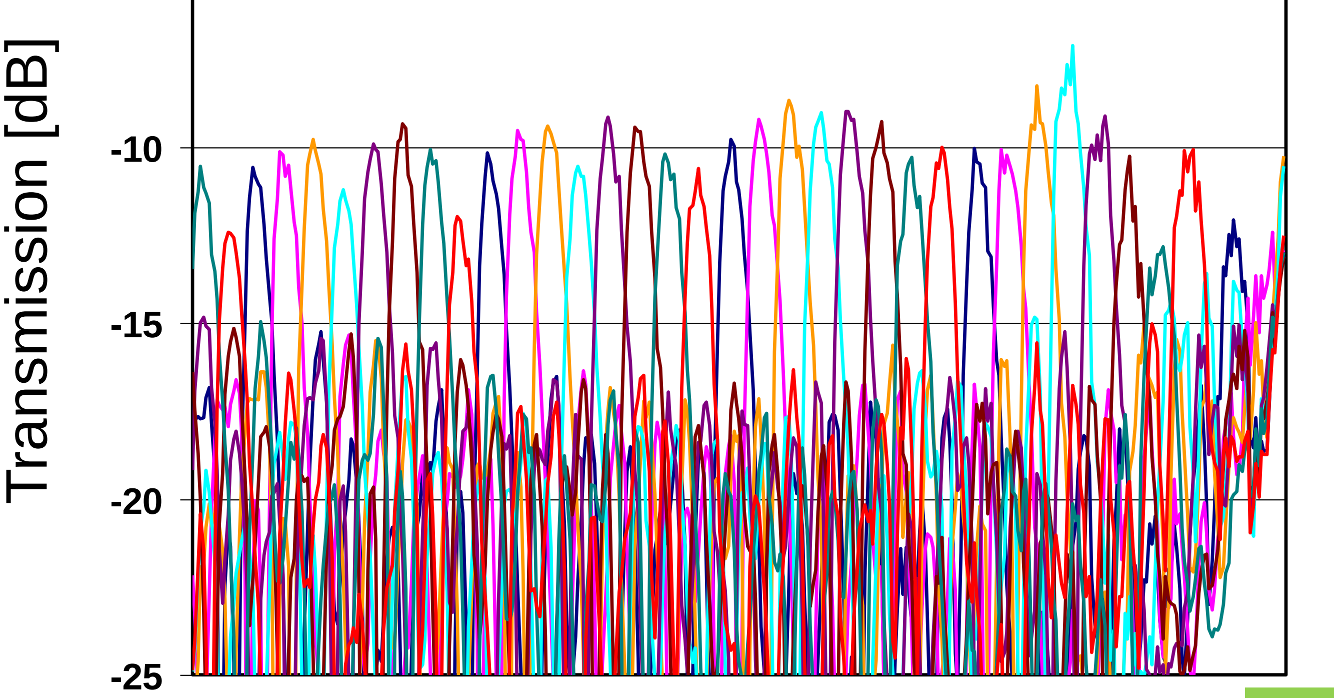
Arrayed waveguide grating routers

Original devices



Compact, but …

- High loss (8dB)
- High crosstalk (only 7dB down)



Dumon e.a. , GFP 2004

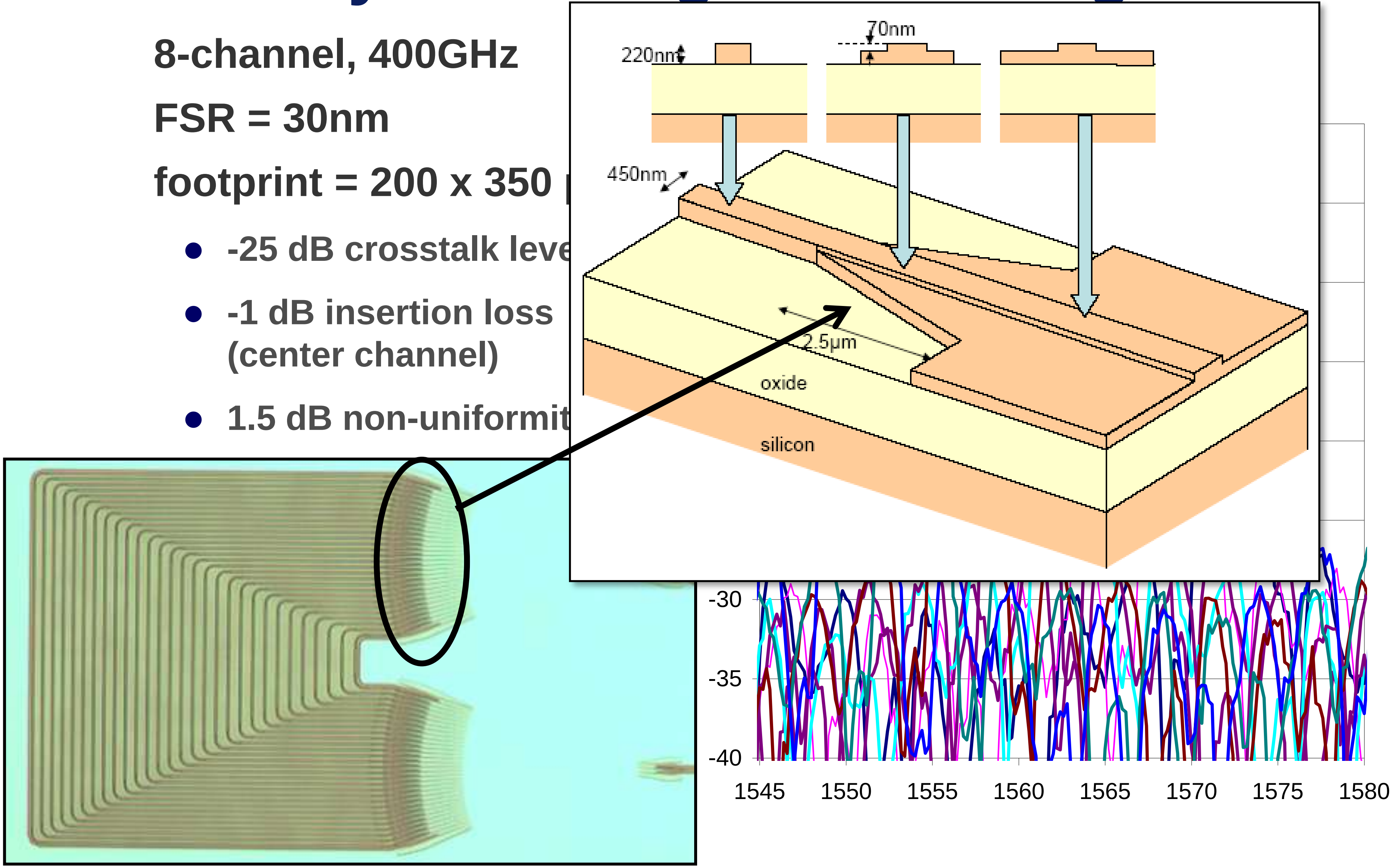
Arrayed Waveguide Grating

8-channel, 400GHz

FSR = 30nm

footprint = 200 x 350

- **-25 dB crosstalk leve**
- **-1 dB insertion loss (center channel)**
- **1.5 dB non-uniformit**



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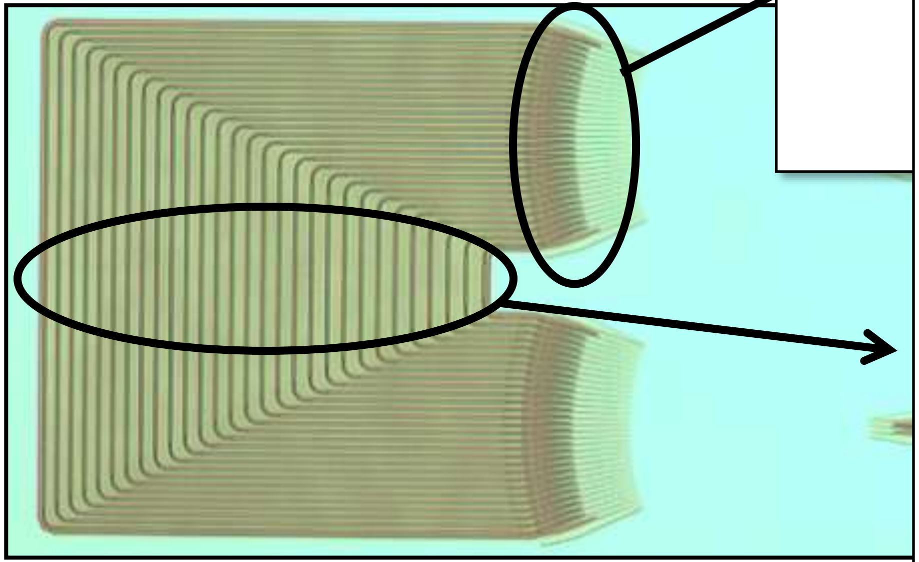
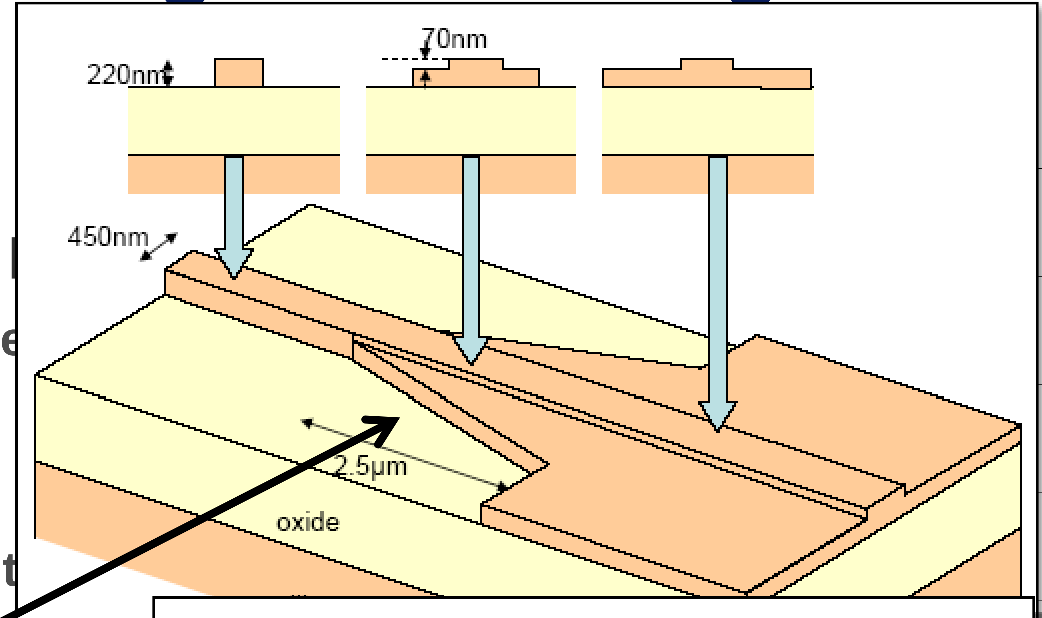
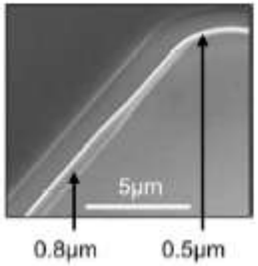


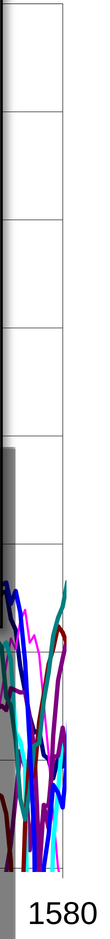


Decrease phase errors

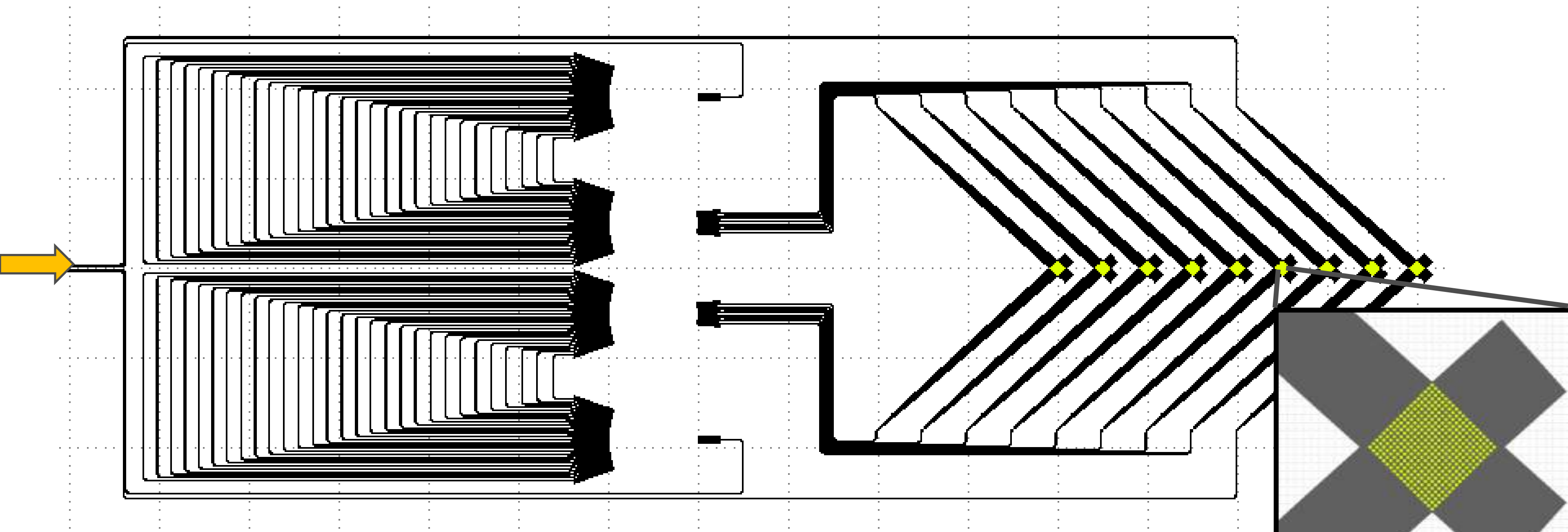
- **Use wider waveguides**

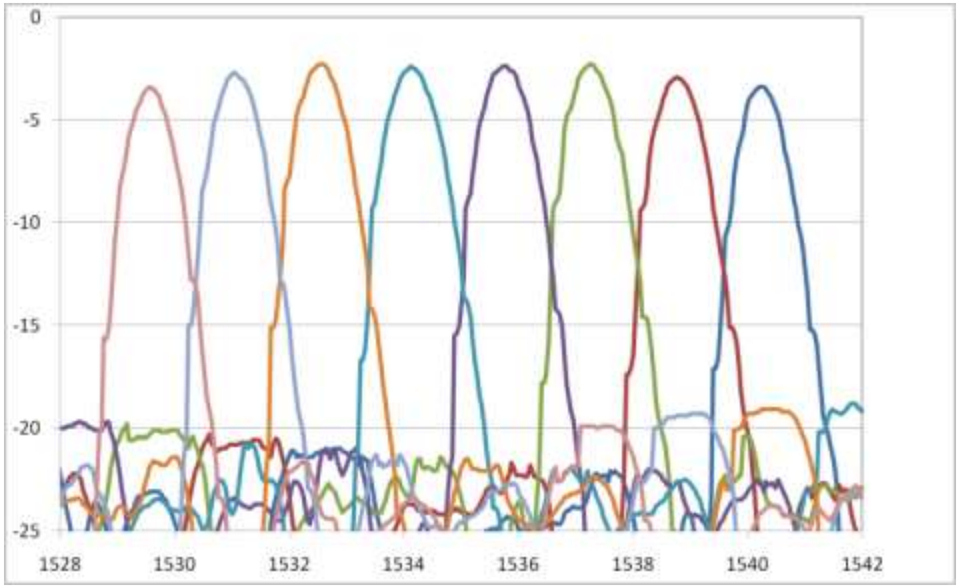


- **Align waveguides to grid**
- **See also:** **P. Dumon, PhD thesis UGent 2007 (http://photonics.intec.ugent.be)**



Polarization independent operation

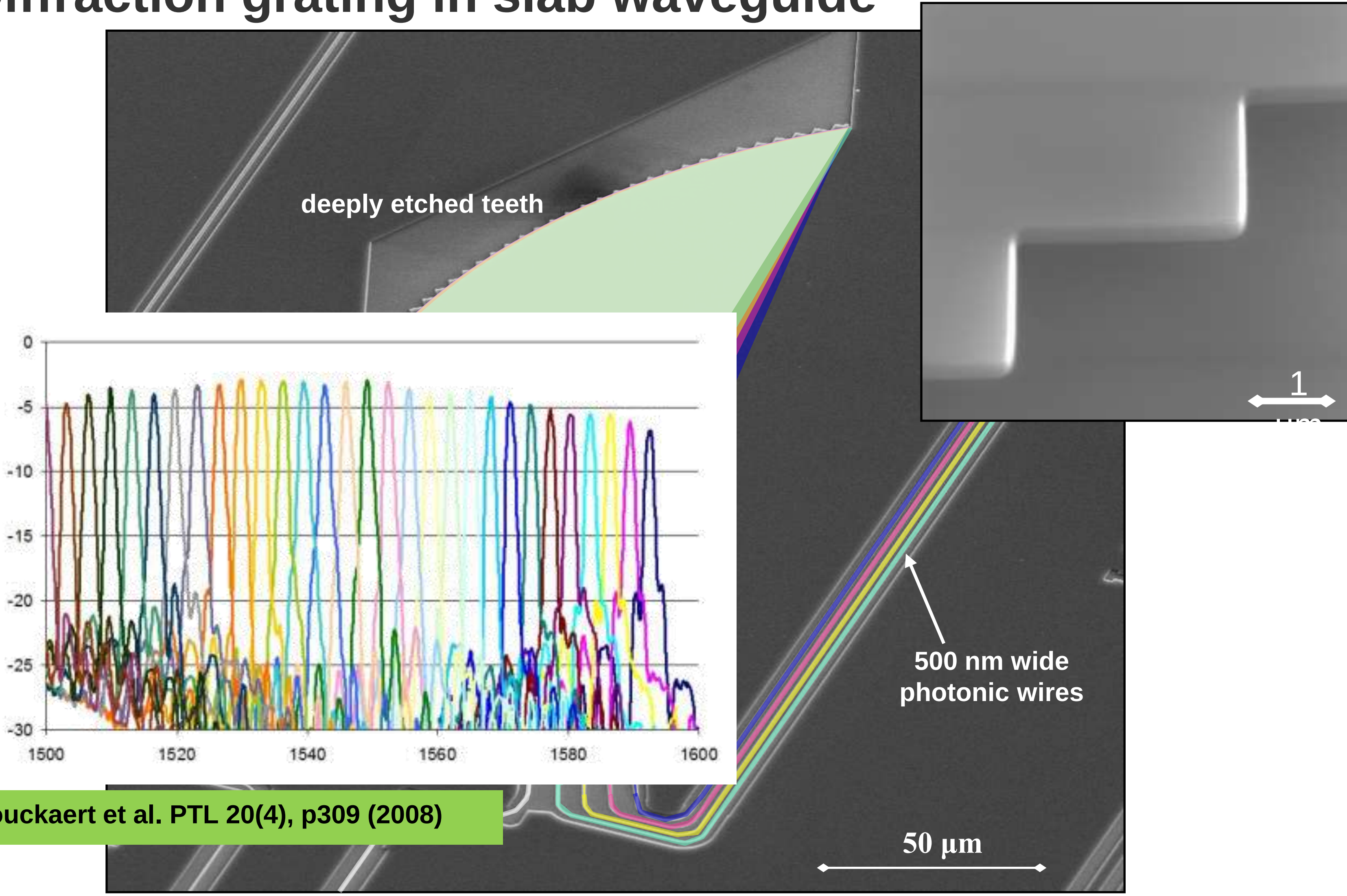




- 8 x 200 GHz
- IL = 2.5-3.5dB
- PDL = 0.5-2dB

Planar Concave Gratings

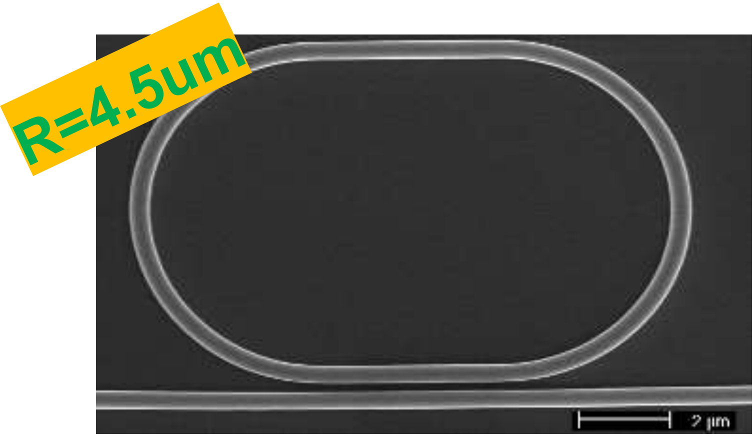
Diffraction grating in slab waveguide

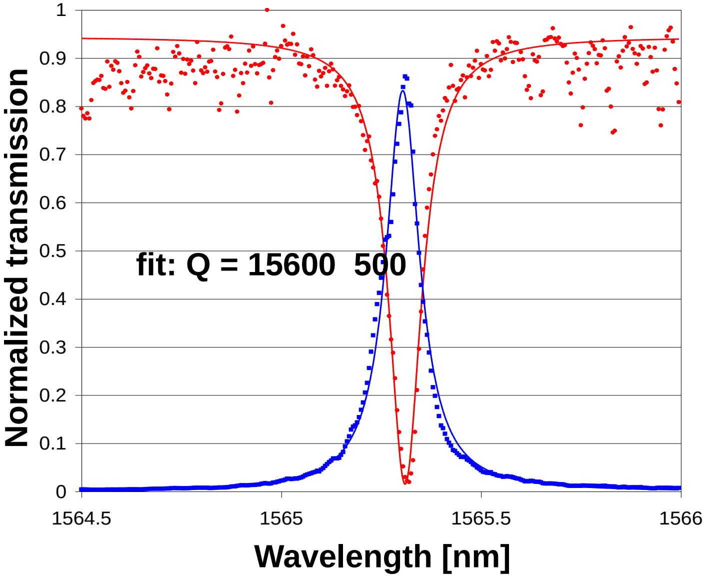


J. Brouckaert et al. PTL 20(4), p309 (2008)

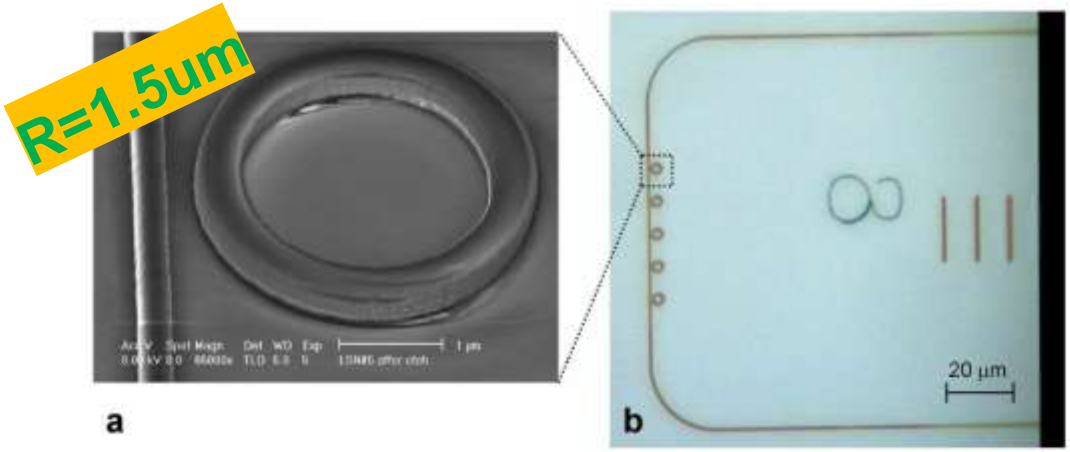
J. Brouckaert et al. JLT 25(5), p1269 (2007)

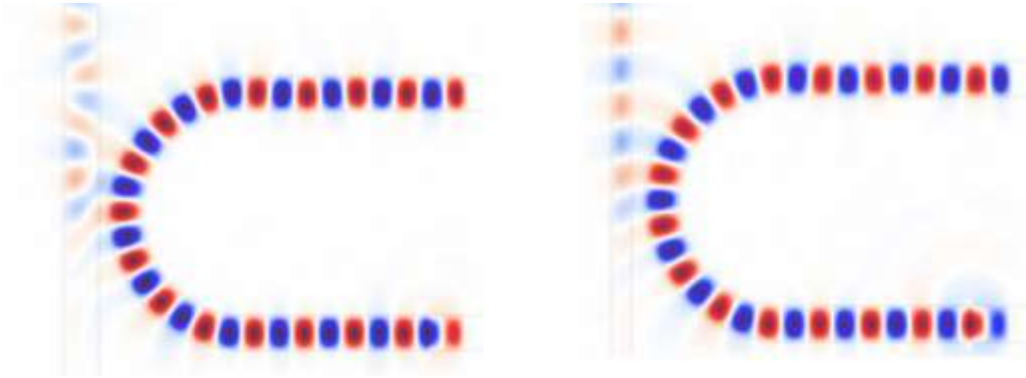
Ring resonators

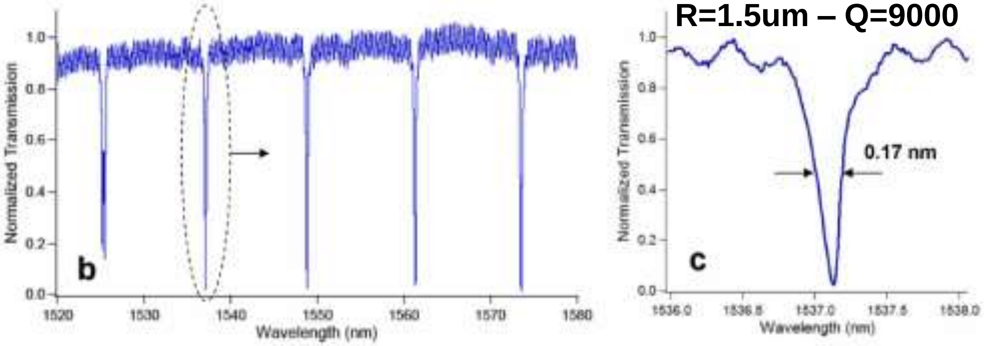




Bogaerts e.a. , JSTQE 16, 33-44 (2010)





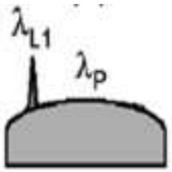


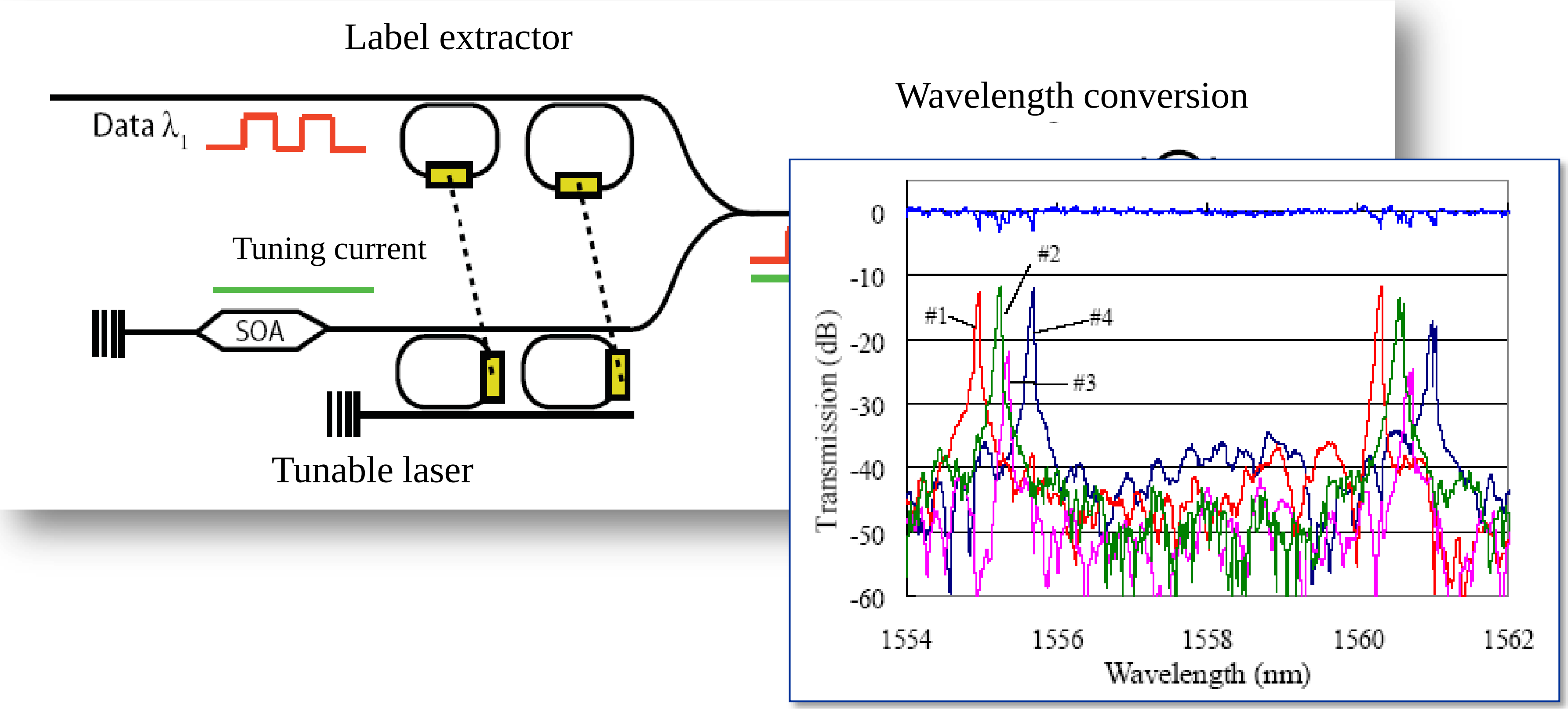
Xu e.a. , OE 16, pp 4309 (2008)

Ring resonators

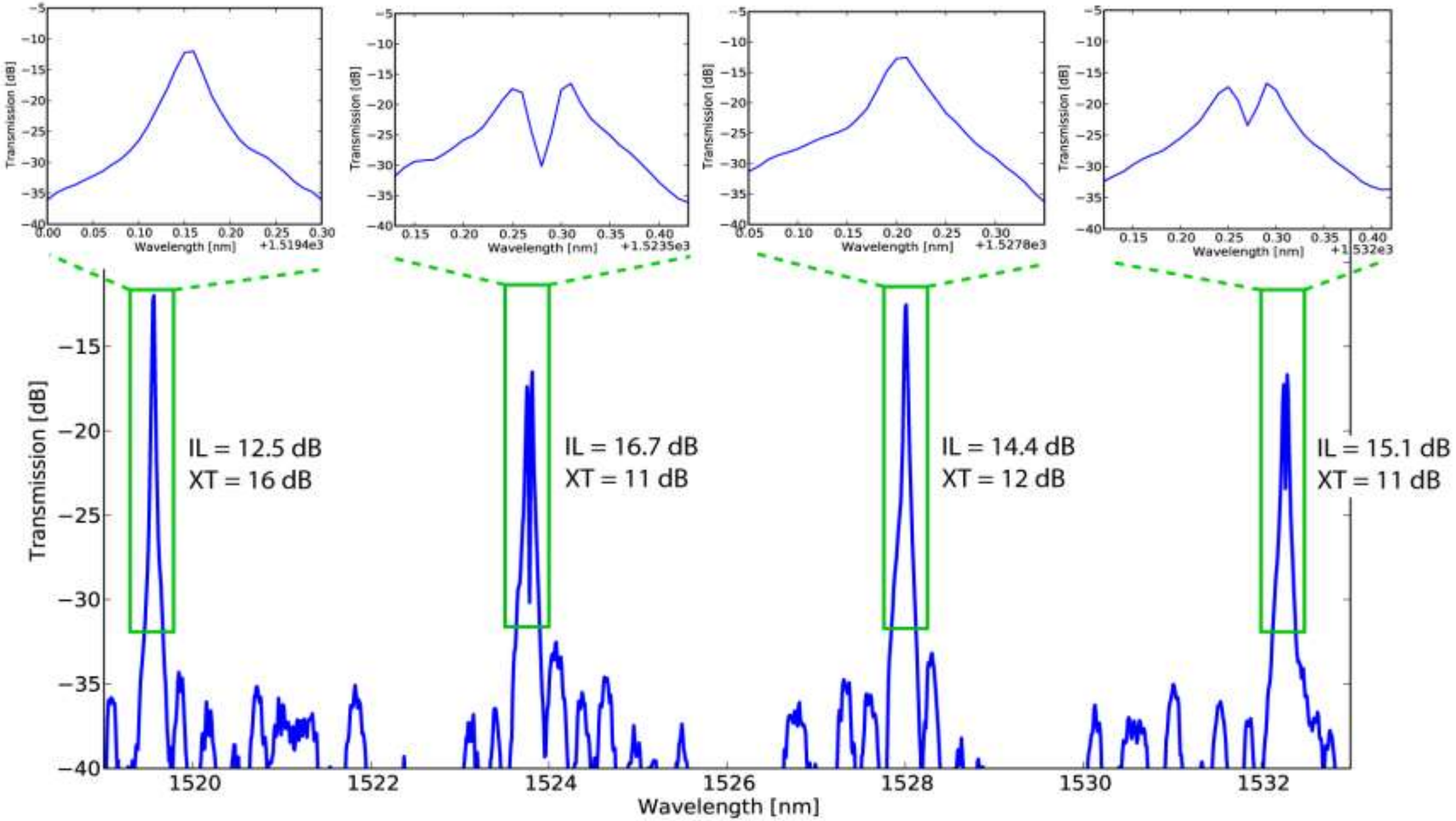
Ring resonators for label extractor

- EU-project BOOM
- Need 0.1nm bandwidth filter
- Use silicon ring resonator ??





TE-Microring meeting BOOM specs? NO



R = 20um, gap = 400nm

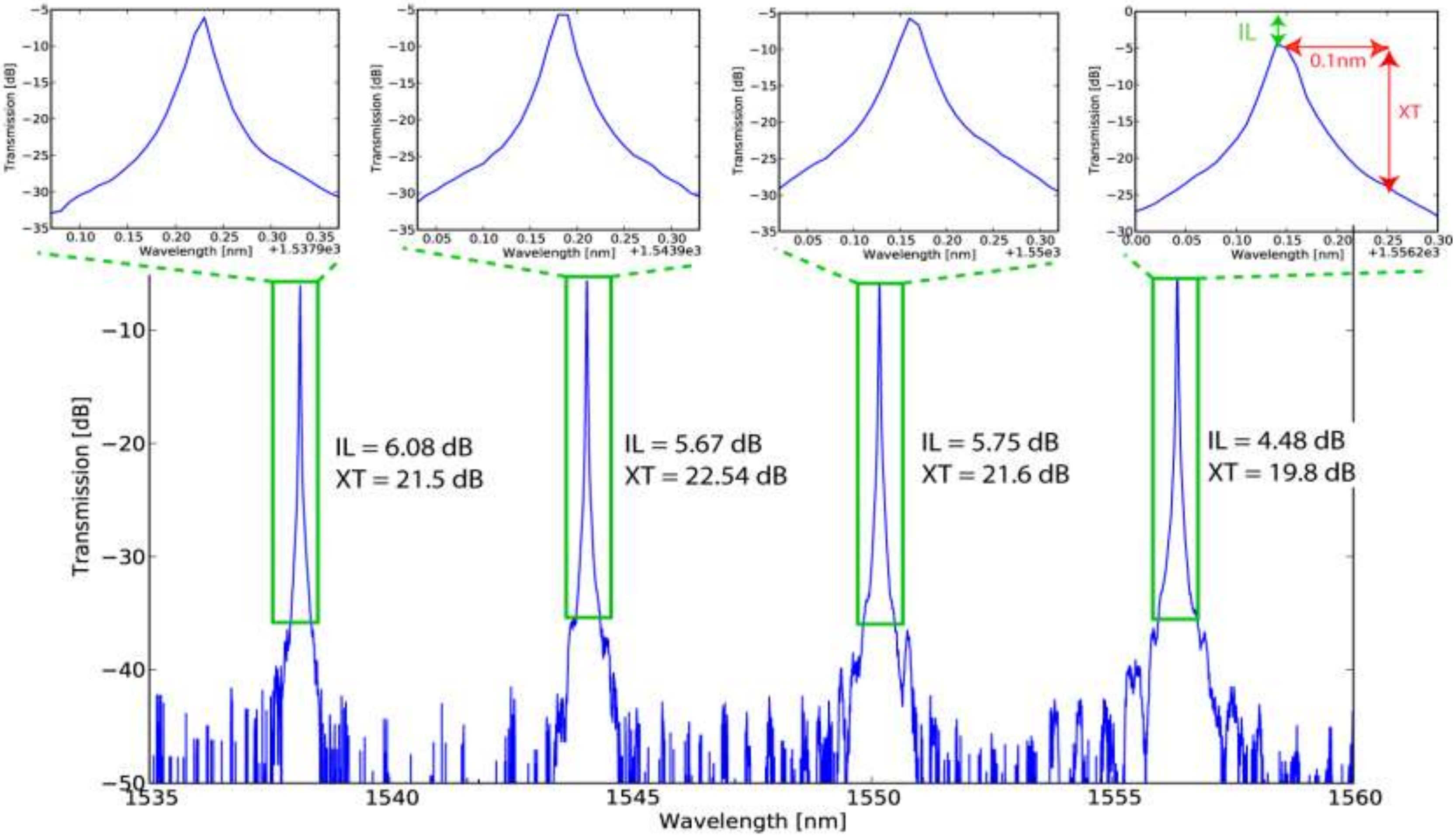
Ring resonators conclusion

TE ring resonators

- Very sensitive to random back scattering
- Behaviour very unpredictable
- High losses

TM ring resonators ?

TM-Microring meeting BOOM specs? YES !



R = 20um, gap = 1um

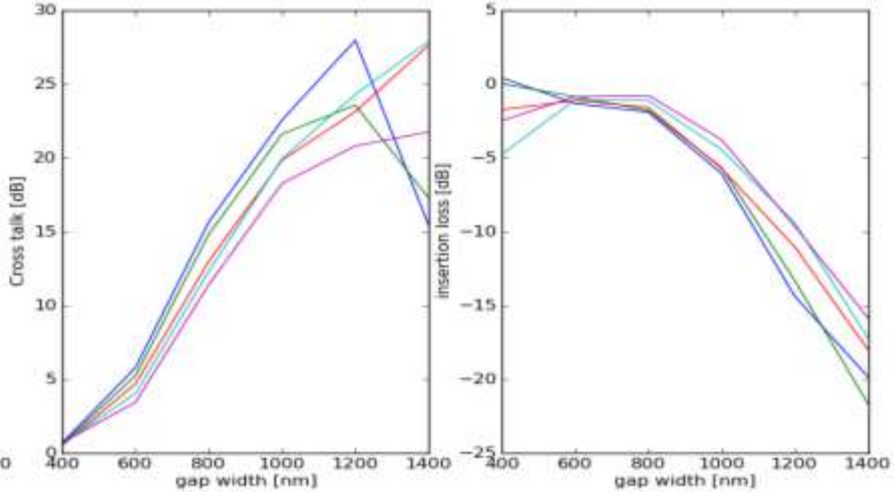
Ring resonators conclusion

TE ring resonators

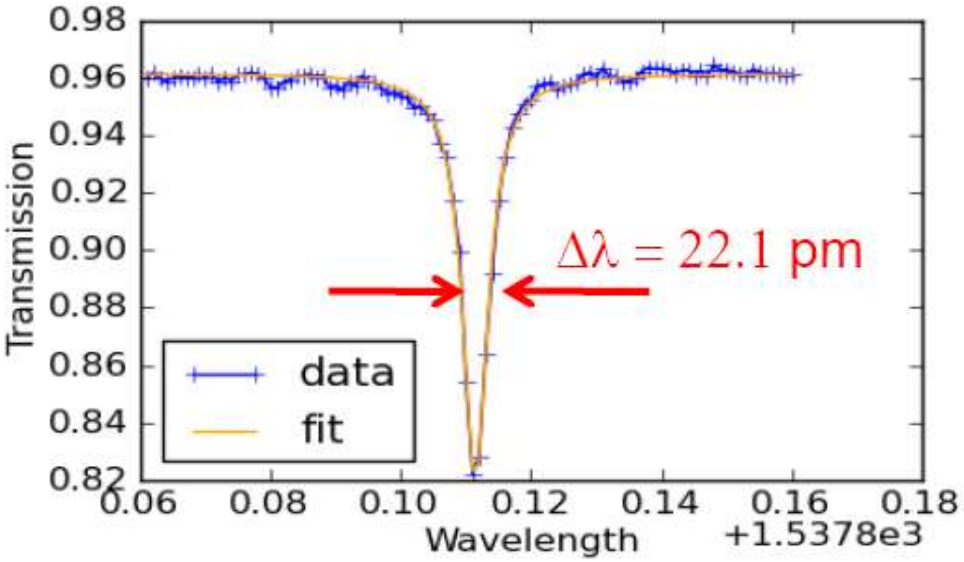
- Very sensitive to random back scattering
- Behaviour very unpredictable
- High losses

TM ring resonators

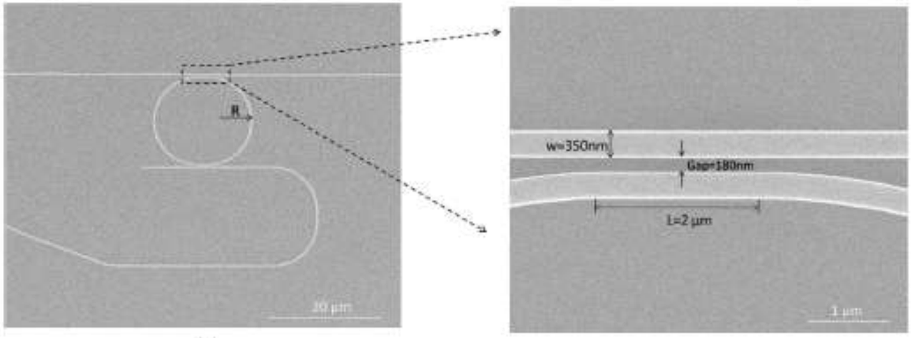
- Lower confinement at side walls
- Lower loss, lower back scattering
- Record high Q values demonstrated (Q_i=340.000)



DeHeyn e.a. , submitted to OFC 2011



Temperature de



Standard devices:

- 80pm/K variation of resonanc
- **Solution**: use polymer overlay with adapted waveguide structure

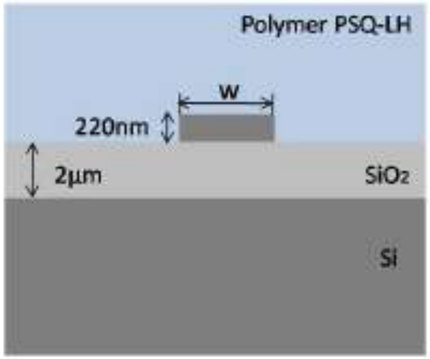
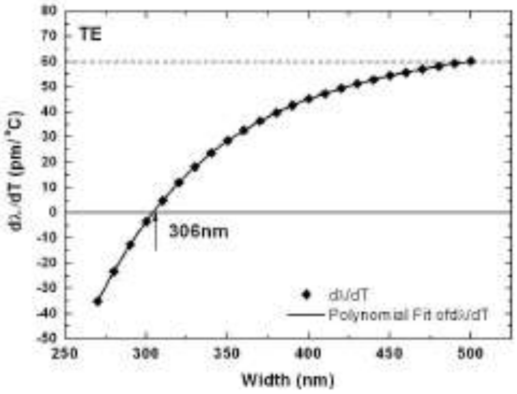
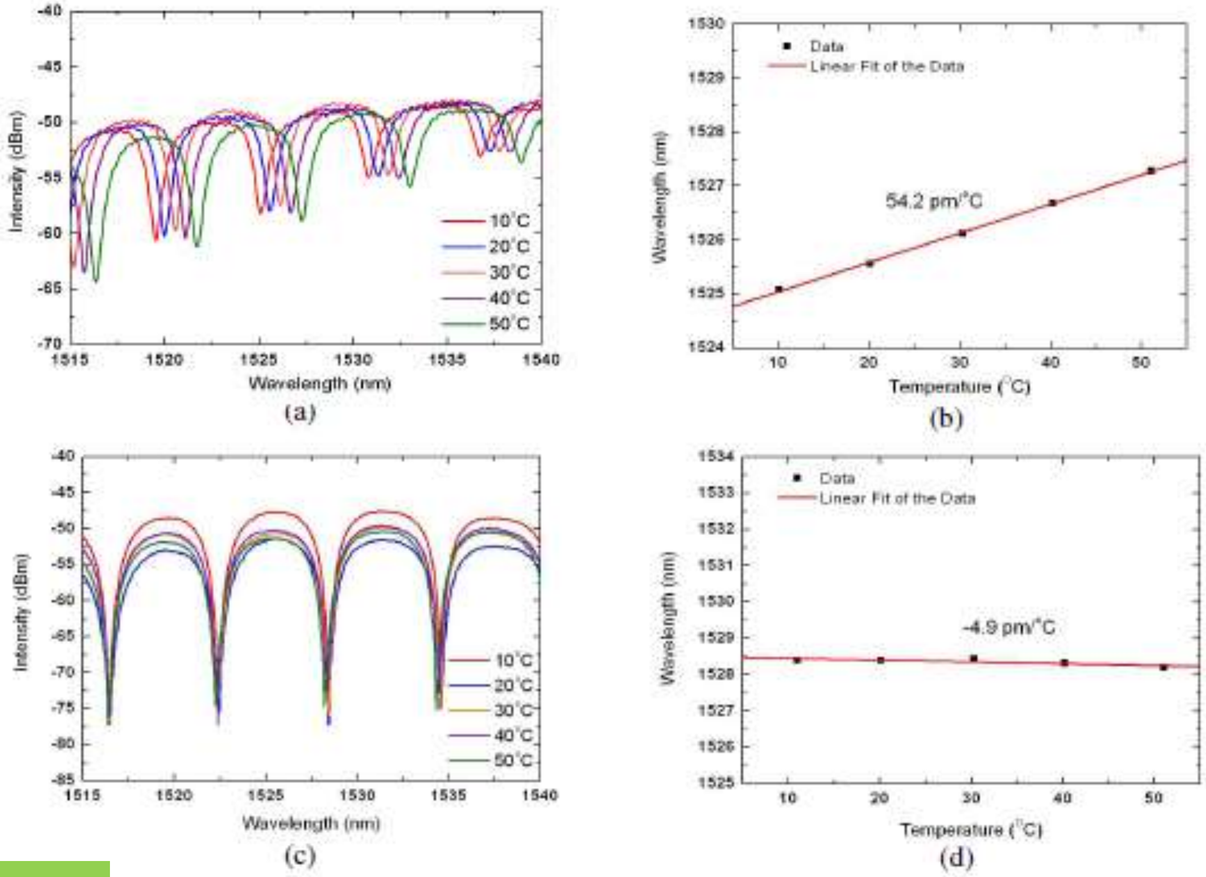


Fig. 1. SOI waveguide cross-section structure





(a)

(b)

(c)

(d)

Teng e.a. , OE 17, 14627-14633 (2009)

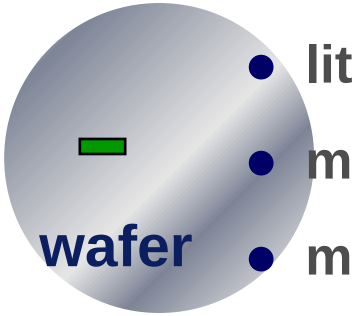
Reproducibility

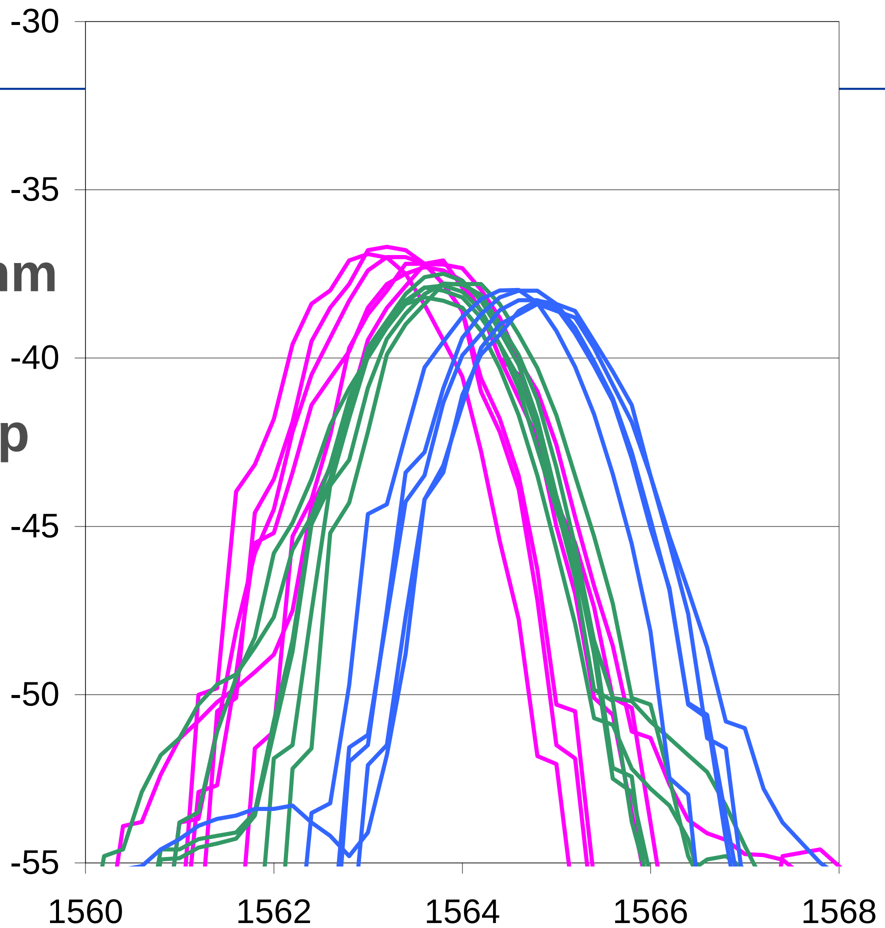
18 identical AWGs

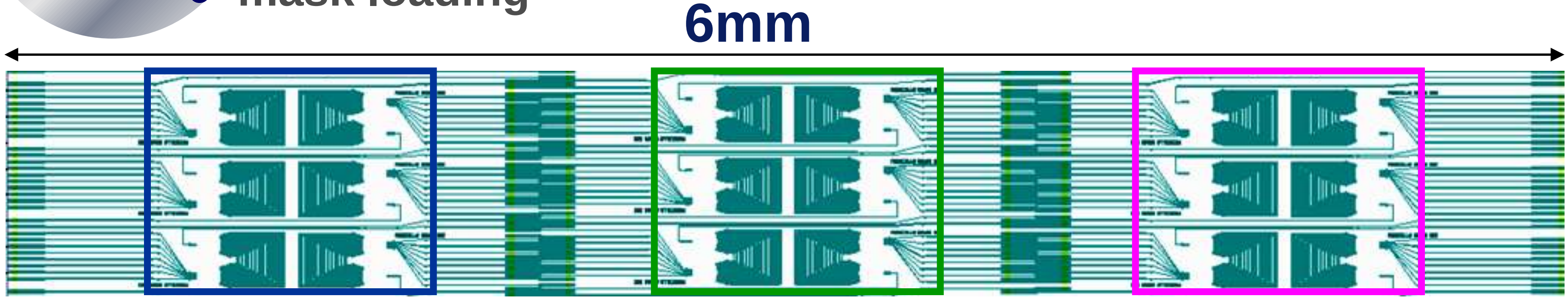
- shift in channel peak ~ 2.5nm
- strong correlation with location of the AWG on chip

Possible causes

- center-to-edge on wafer
- lithography scanning
- mask fabrication
- mask loading





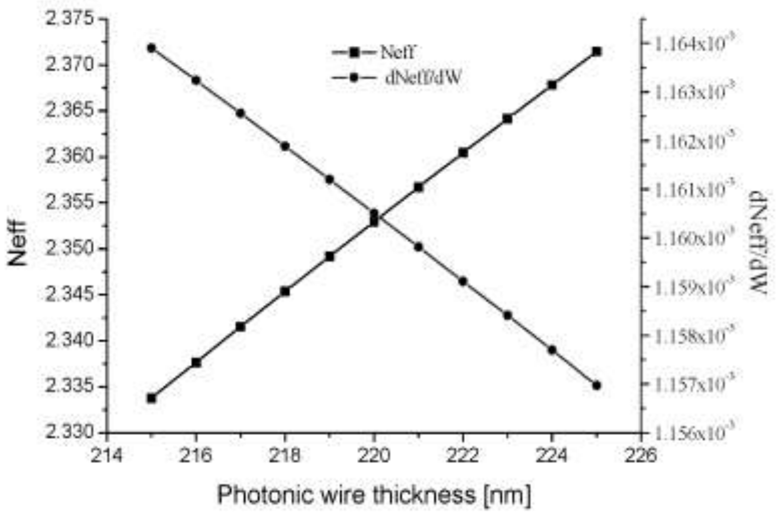


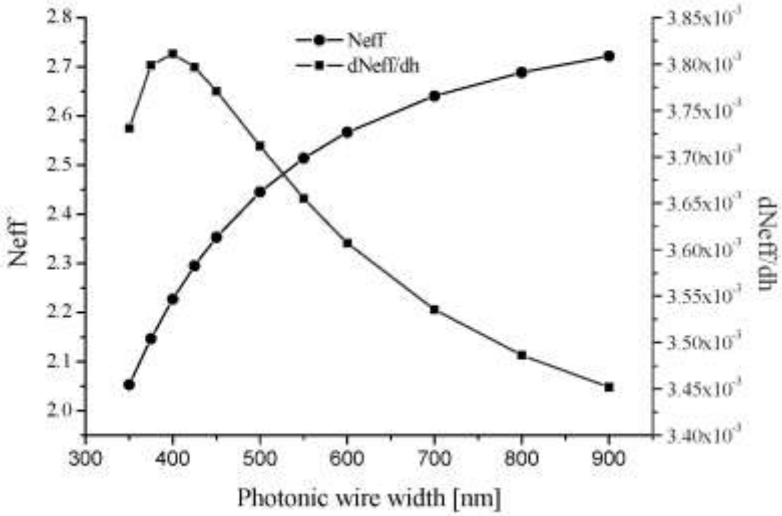
See papers Shankar Selvaraja at http://photonics.intec.ugent.be

Challenges: sensitivity

Fabrication:

- Sensitivity to fabrication errors





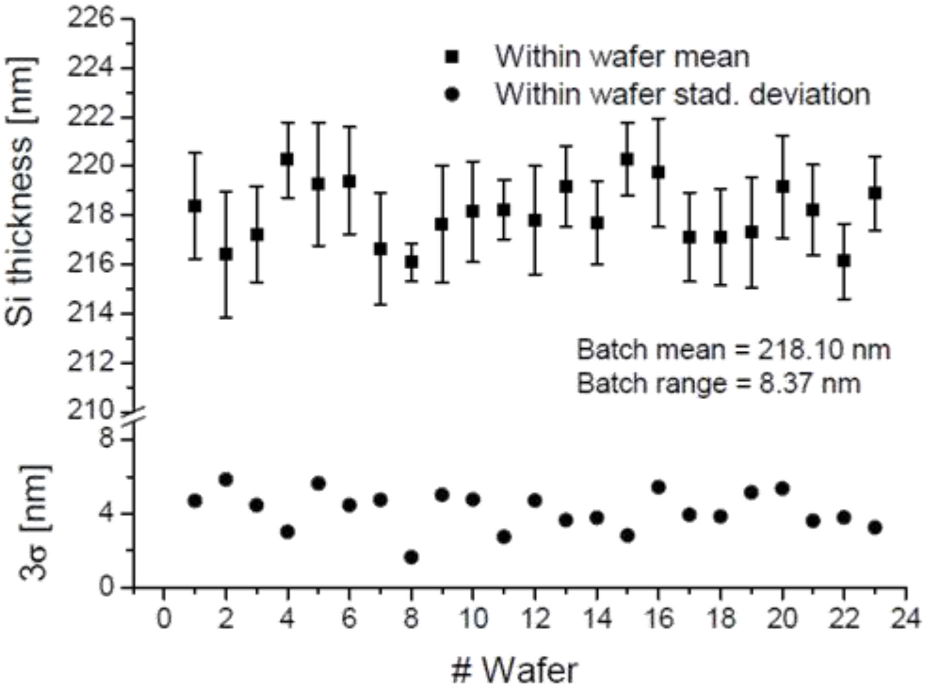
Roughly: 1nm variation in line width / thickness

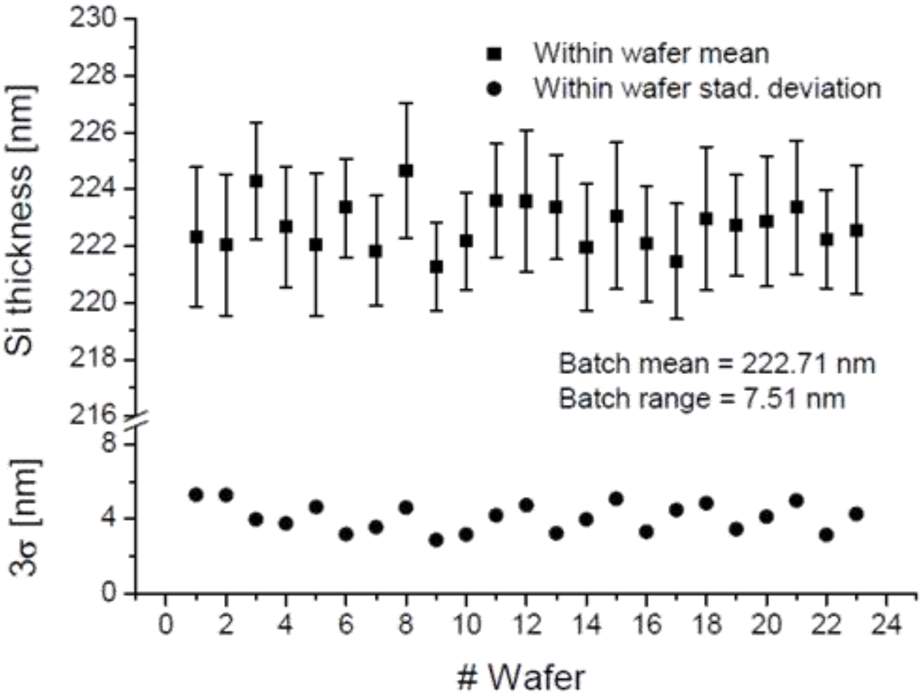
1nm variation in central wavelength of device

Challenges: sensitivity

Influence of starting wafer (SOITEC wafer, 220nm Si, 2um SiO_2)

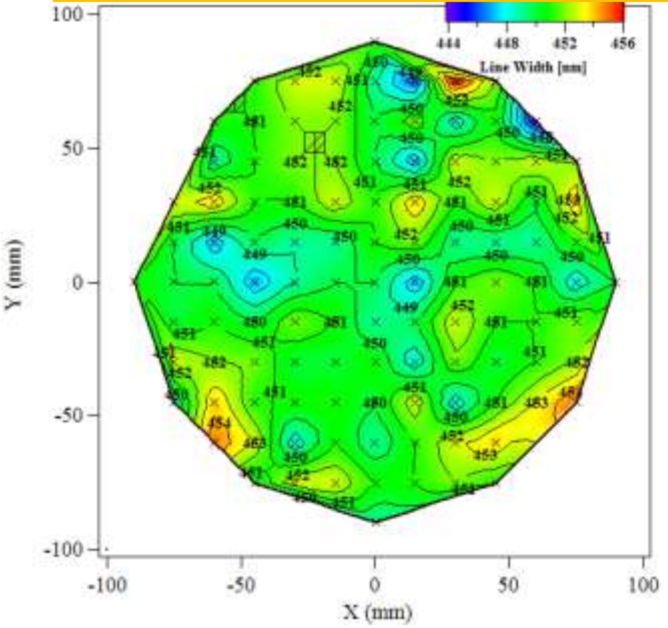
- Silicon layer thickness varies widely
  - Batch to batch
  - Wafer to wafer
  - Within wafer



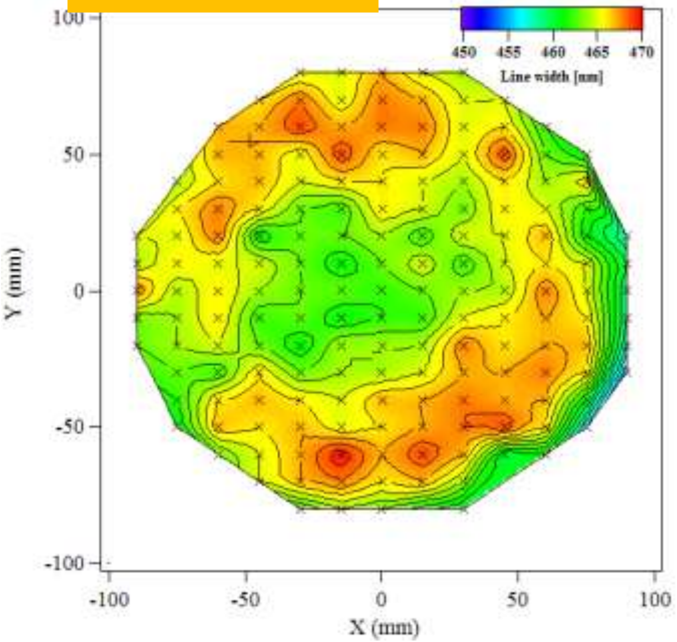


Challenges: sensitivity

After Litho (DUV 193nm)



After Etch

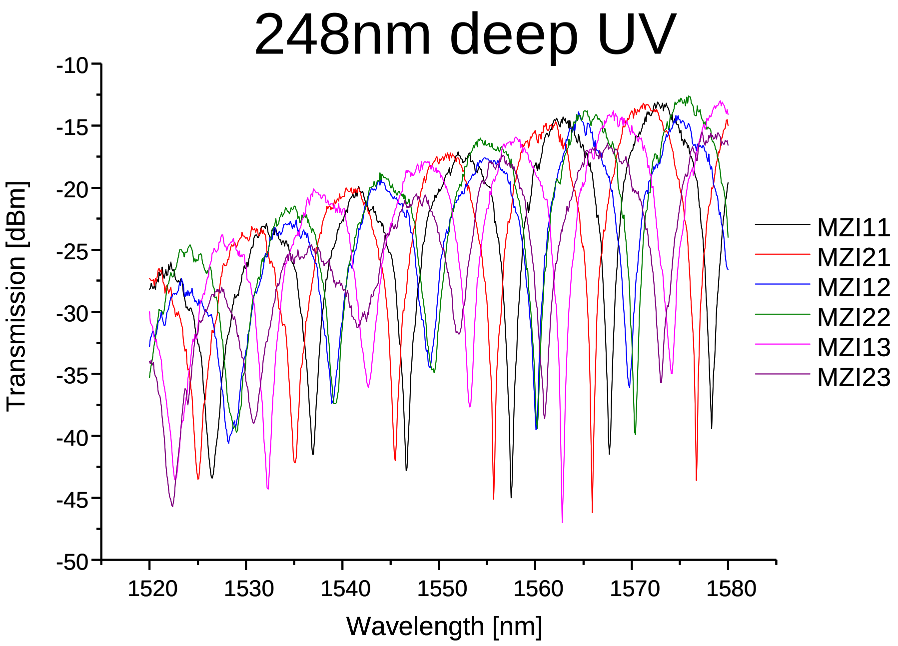


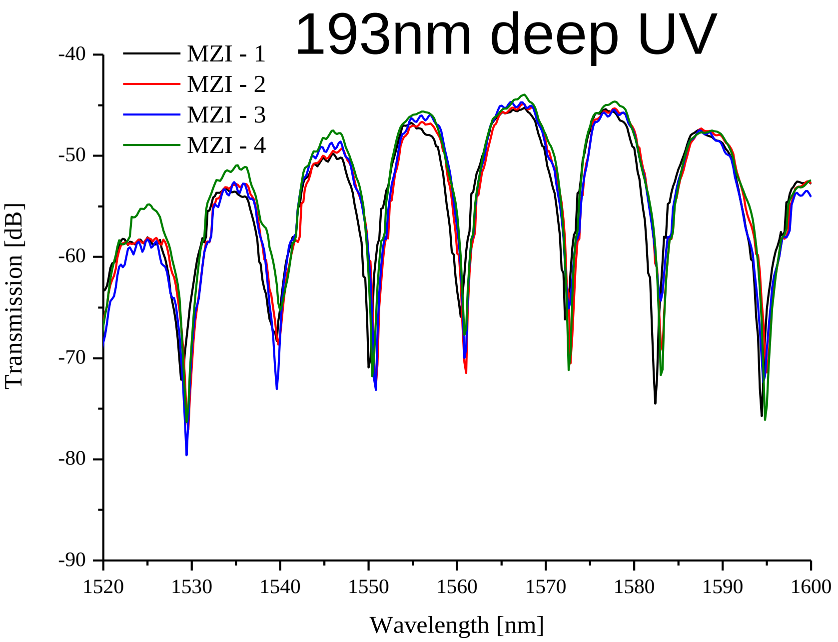
Variations in linewidth over 200mm wafer

- Less than 1% line width variation over 200mm wafer
  - Much better than typical CMOS specs
  - 1% is still 5nm !!
  - Pure passive, further post processing may increase problem (e.g. stress …)

Challenges sensitivity

Influence of fabrication technology


248nm deep UV


193nm deep UV

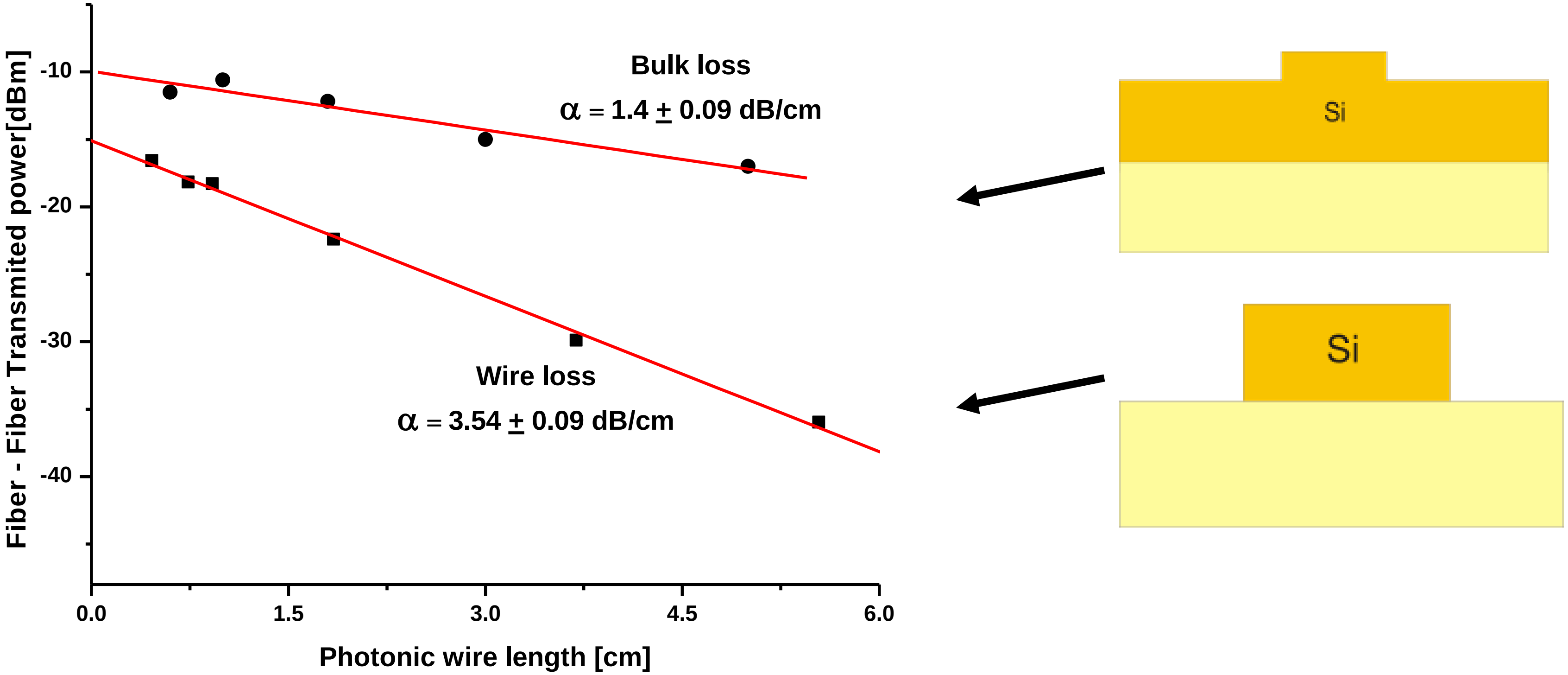
- 6 MZI’s located 2mm apart
  - 248nm very far of from specs
  - 193nm <2nm variation over die

Amorphous silicon wires

Low-temperature PECVD a-Si:H deposition

Low material losses

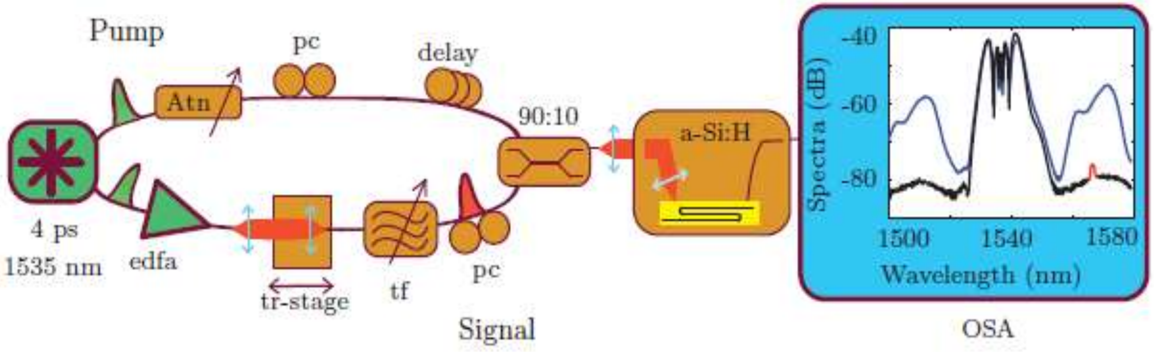
- deep-etch wire (480nm width): 3.54dB/cm
- shallow rib waveguide: 1.4dB/cm

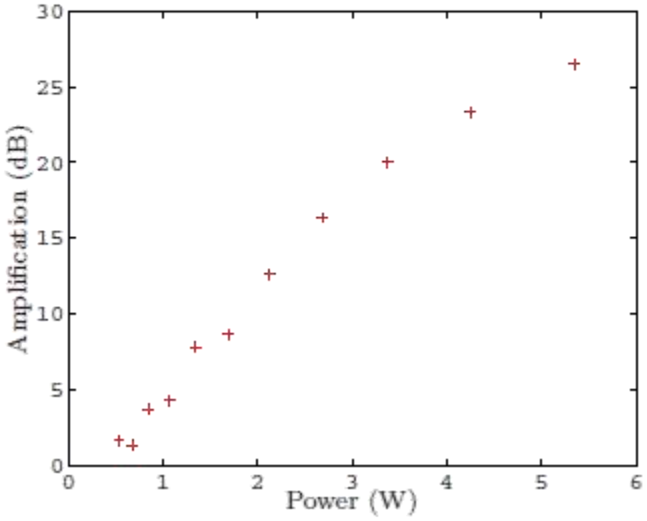


Amorphous silicon wires

Amorphous silicon

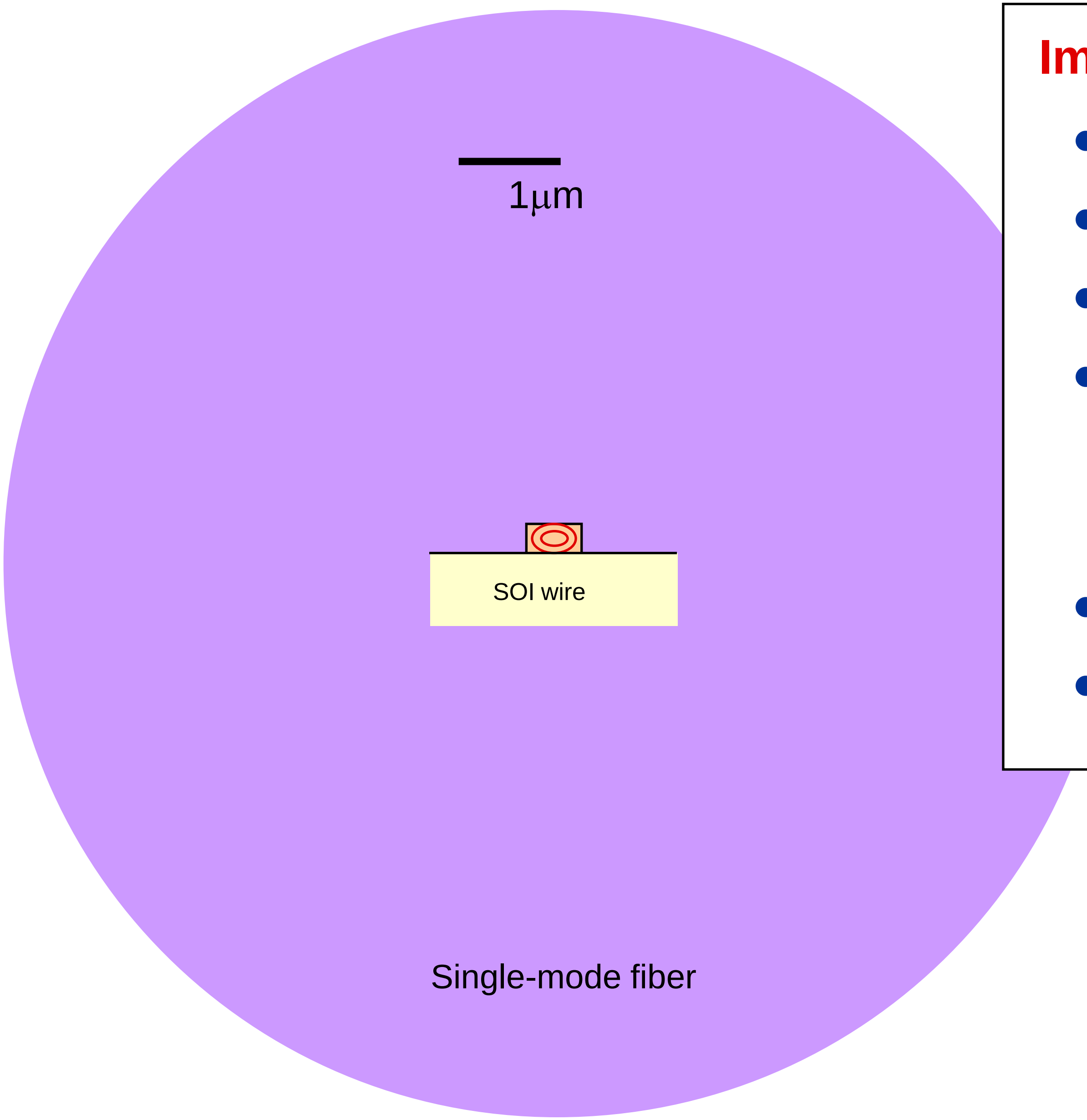
- Shows improved non-linear performance
  - Lower non-linear absorption
  - Higher non-linear n_2
- Demonstrated 26dB parametric gain (on-chip)





Results presented at IEEE Photonics Society annual meeting (Denver, 2010)

Coupling into SOI nanophotonics

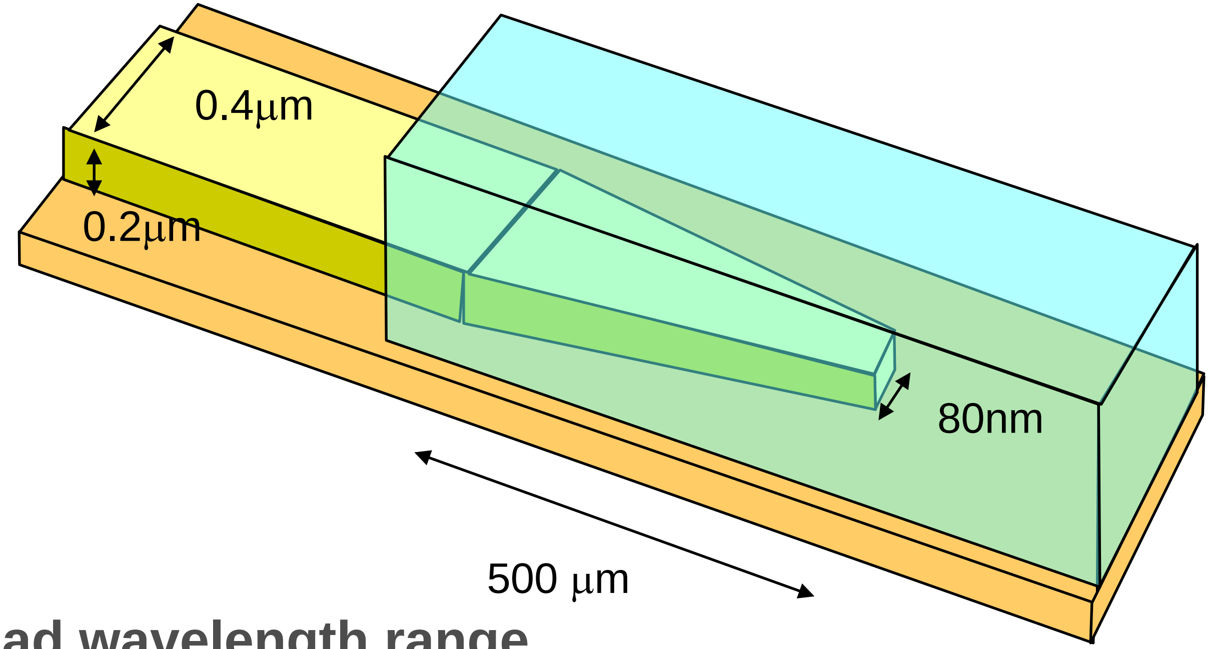


Important:

- Low loss coupling
- Large bandwidth
- Coupling tolerance
- Fabrication
  - Limited processing
  - Tolerant to fabrication
- Low reflection
- Polarization ?

Coupling to fiber – Inverse taper

Inverse taper



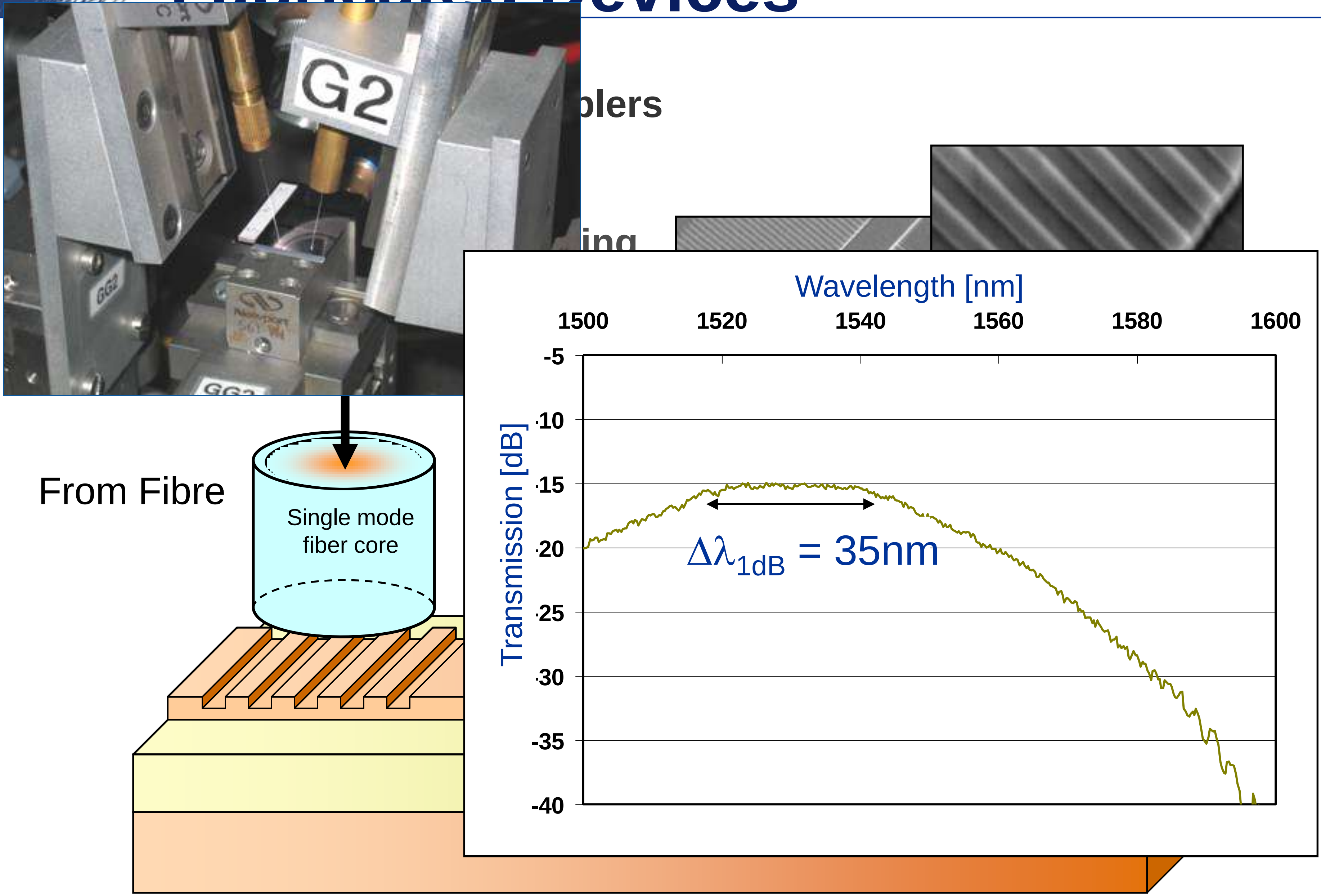
polished
facet

- **Broad wavelength range**
- **<1dB loss (to lensed fibre)**
- **Easy to fabricate (if you can do the tips)**
- **Low facet reflections**
- **Cleaving or polishing needed**

Fabricated Devices

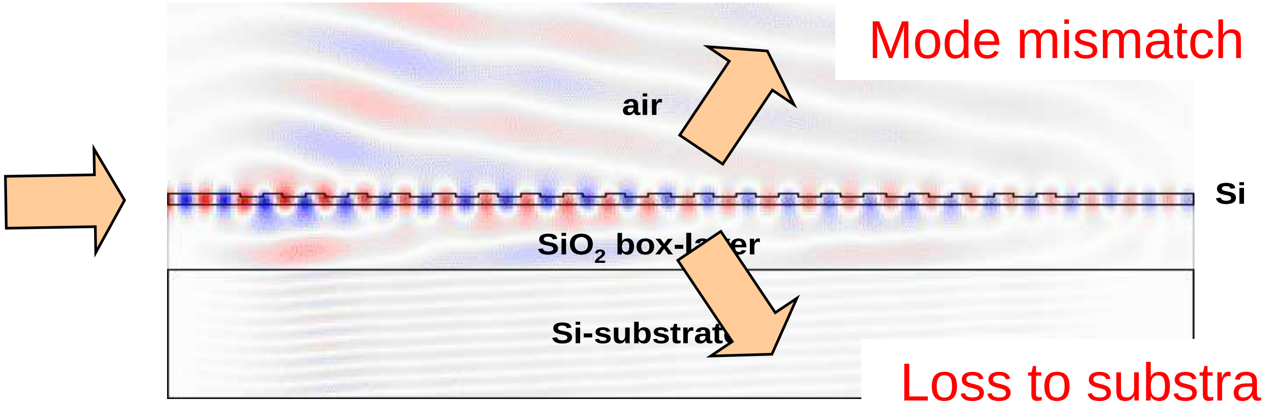
plers

ing



Increase effieciency ?

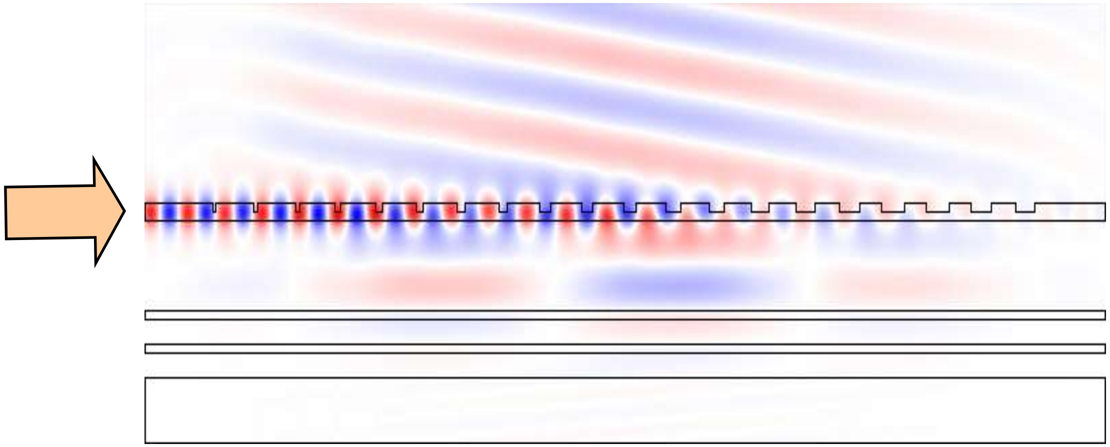
Standard coupler (33%)



Mode mismatch

Loss to substrate

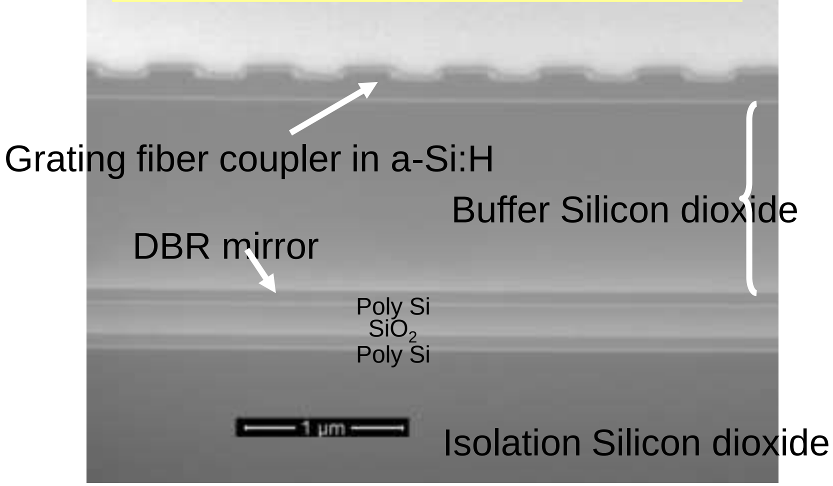
Improvement: add bottom mirror + apodize



90% simulated !

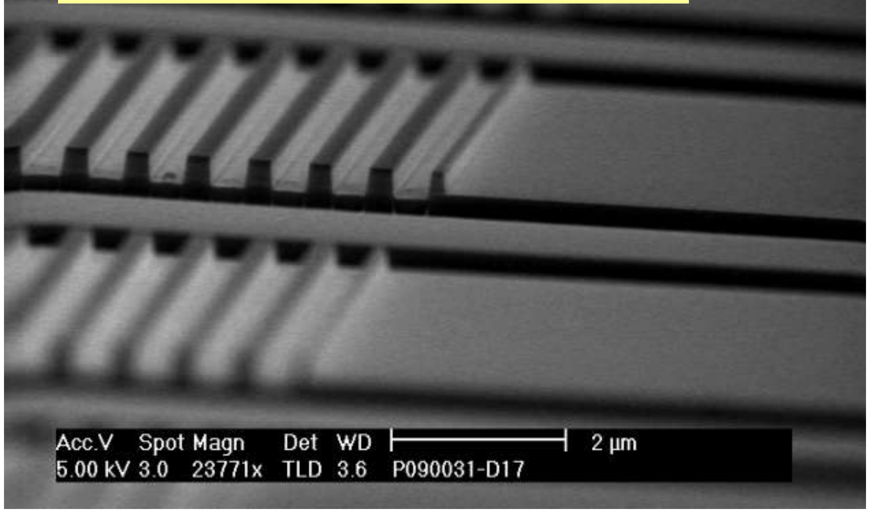
The grating zoo

With bottom DBR (69.5%)



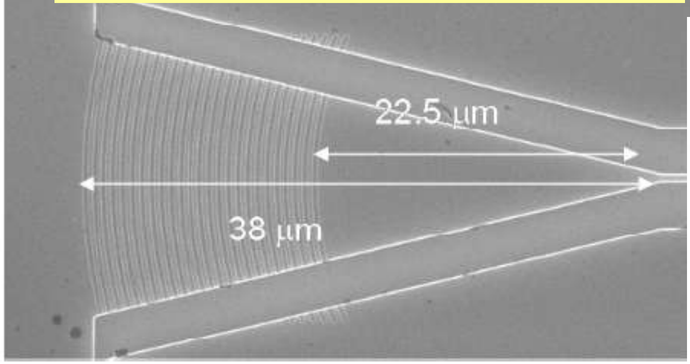
CLEO, 2009

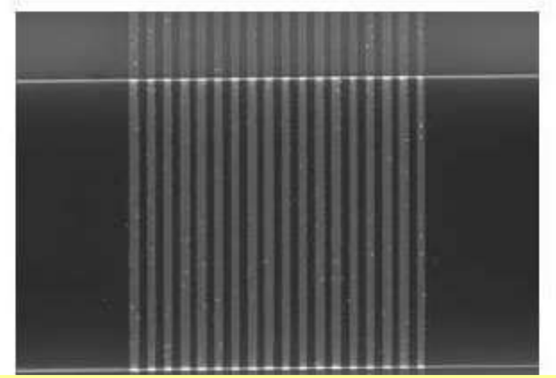
With overlay (69%)



Group IV, 2009

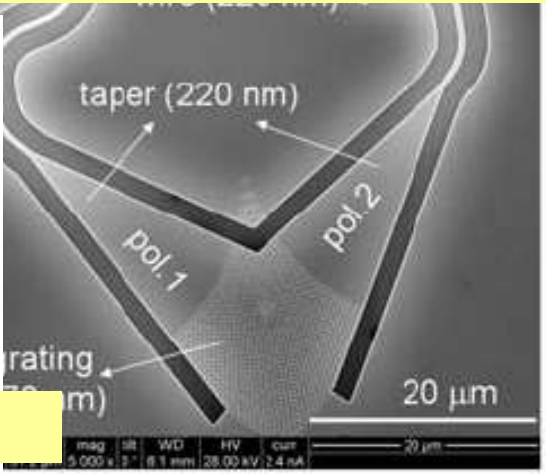
Focussed gratings





Metal gratings

2D gratings (polarization)

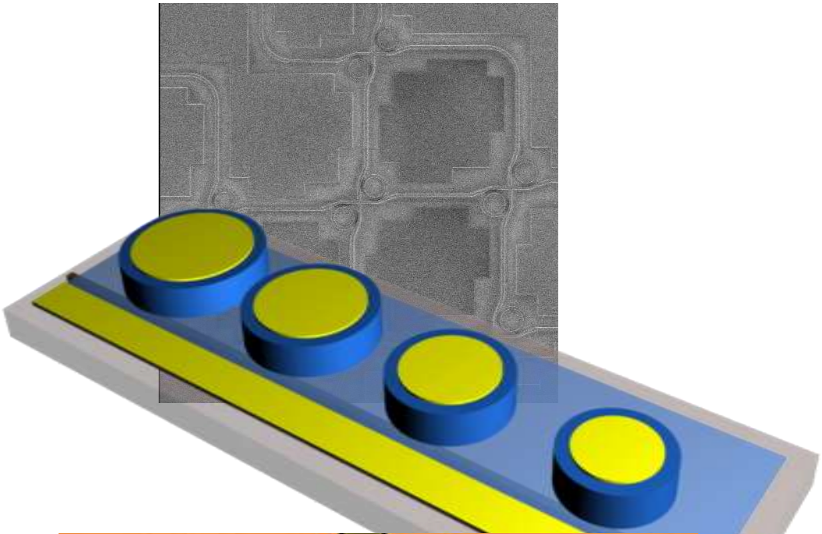


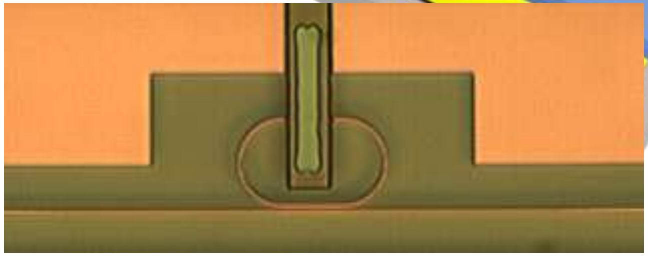
Outline

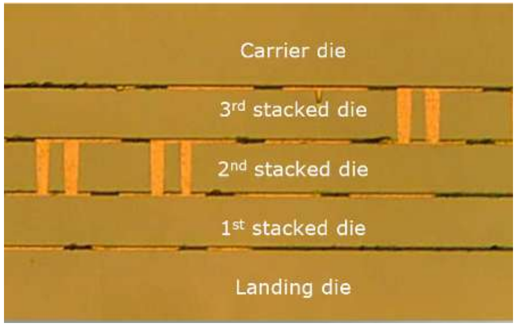
Outline

- Passive routing circuitry
- Multi-wavelength lasers
- Wavelength selective detectors
- Integration with electronics

- Some other applications …
- How to get access to technology





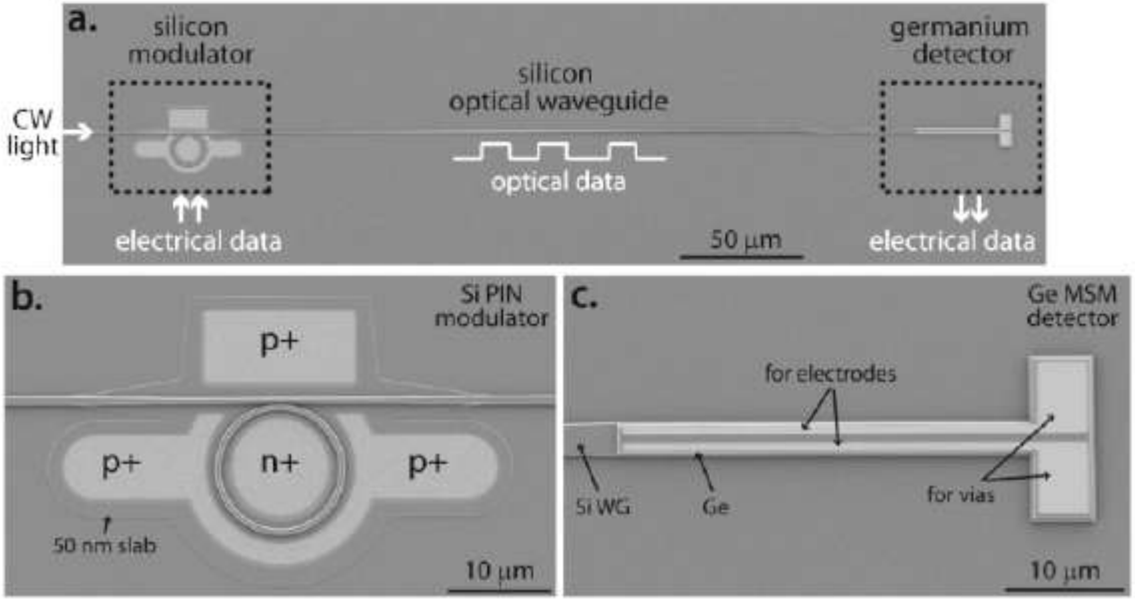


Sources and detectors

How to build the transmitter ?

Option 1: Off-chip source, on-chip modulators

- Standard modulators are big and power hungry !
- Resonant modulators need wavelength alignment !



Chen e.a. , OE 2009, p. 15248

Sources and detectors

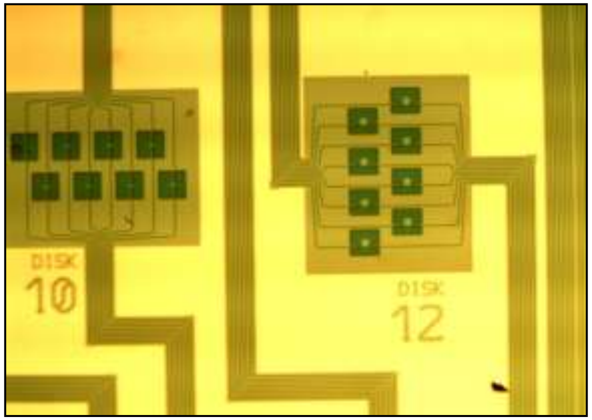
How to build the transmitter ?

Option 1: Off-chip source, on-chip modulators

- **Standard modulators are big and power hungry !**
- **Resonant modulators need wavelength alignment !**
- **Complicated provisioning of CW signal**

Option 2: Directly modulated microlasers on chip

- **Laser = resonator → self-aligned in wavelength**
- **No CW signal bus needed**
- **Integration ? Heat management ? Reliability ?**



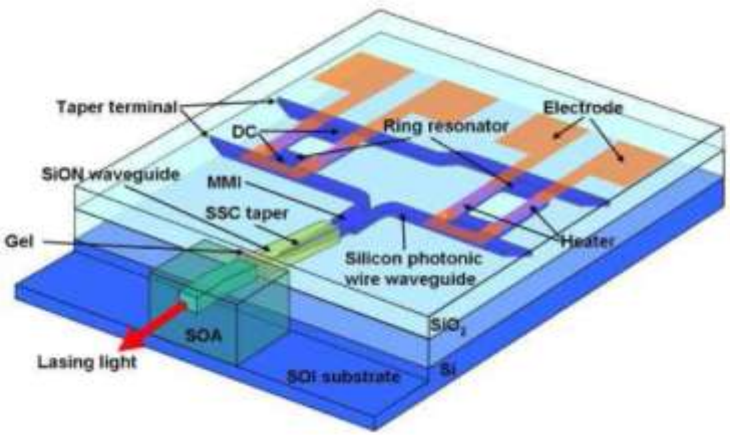
Efficient source on silicon

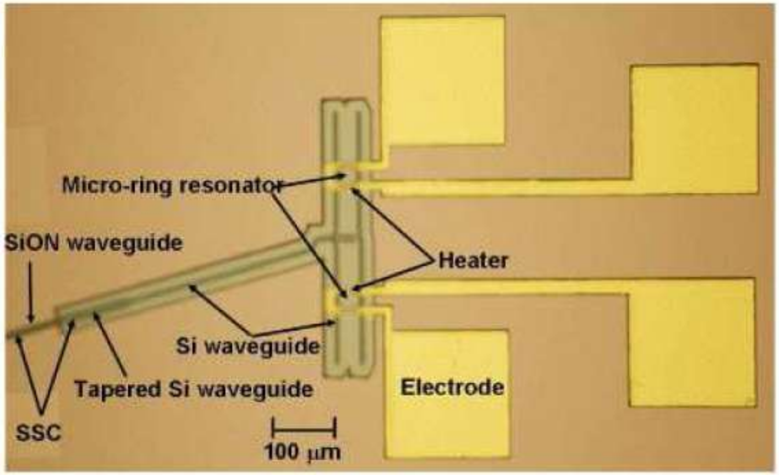
Through hybrid integration ?

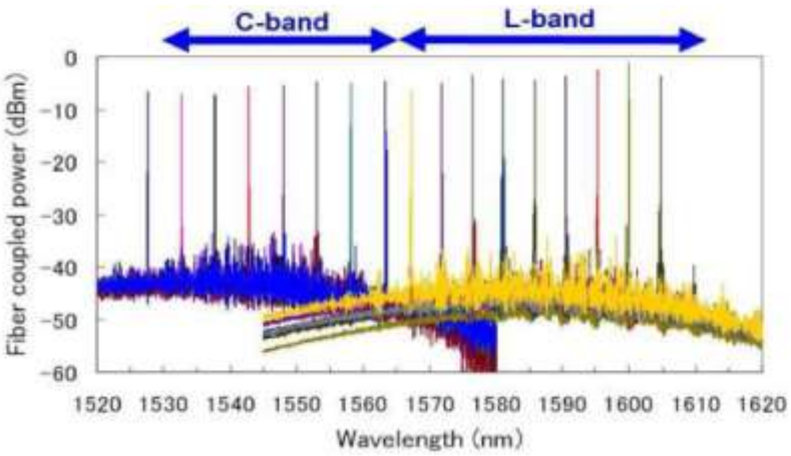
- Integration of preprocessed devices
- Allows pretesting of devices
- Requires sub micron alignment (costly, time consuming)

Sources on Silicon

Hybrid integration (NEC)







Song e.a. OE 17, 14063-14068 (2009).

Efficient source on silicon

Through hybrid integration ?

- Integration of preprocessed devices
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- Requires sub micron alignment (costly, time consuming)

Through monolithic integration ?

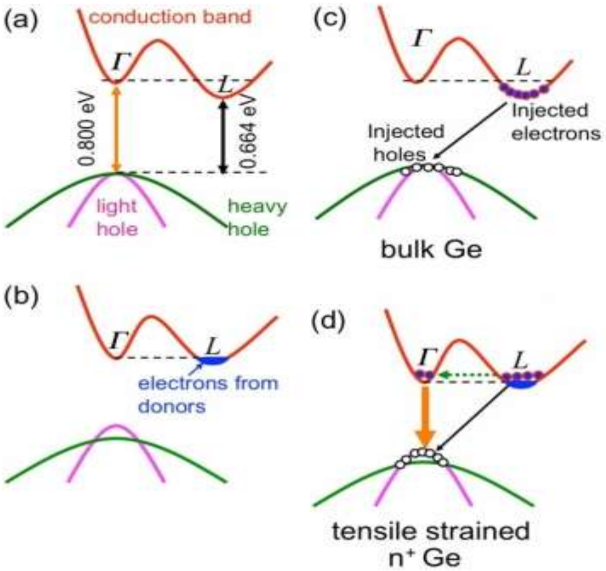
- Epitaxial III-V on silicon, Germanium on silicon, Er-doped silicon …
- Potentially highest density, lowest cost, highest yield
- Currently: low gain and/or high defect number

Sources on Silicon

Monolithic integration

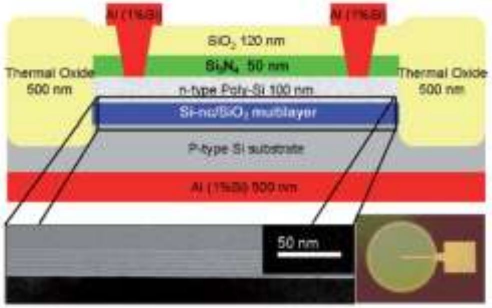
- Waferscale "deposition" of active material

Strained Ge-laser



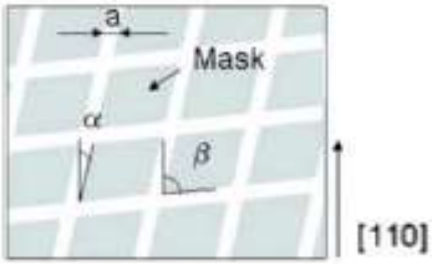
MIT press release

Er-doped Si nanocrystals



Zhizhong, Y. et al. Proc of the IEEE 97, 1250 (2009).

III-V on silicon epitaxy



Junesand e.a., IPRM 2009 pp59

Efficient source on silicon

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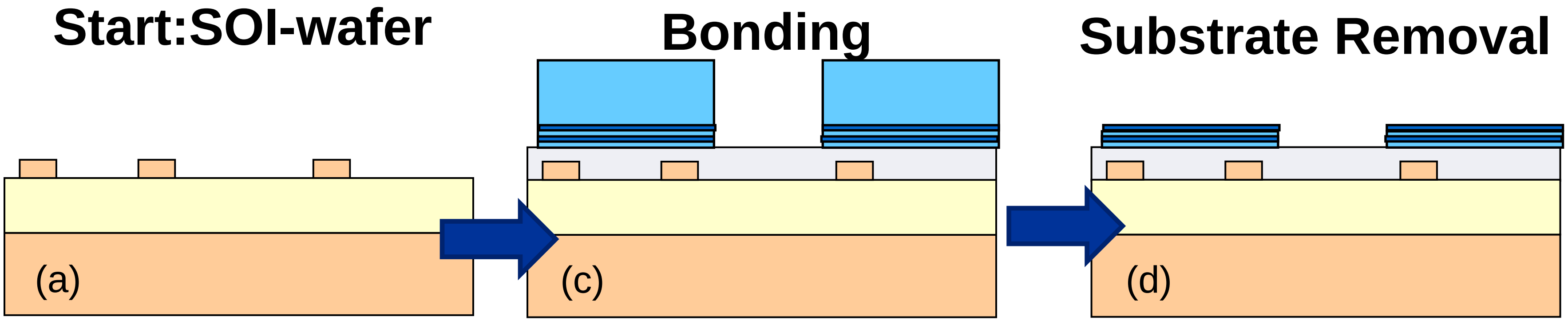
Wafer bonding based heterogeneous integration !

- III-V integration on Silicon using bonding processes
- Collective processing of all devices simultaneously
- Alignment guaranteed by lithography process

What are we talking about ?

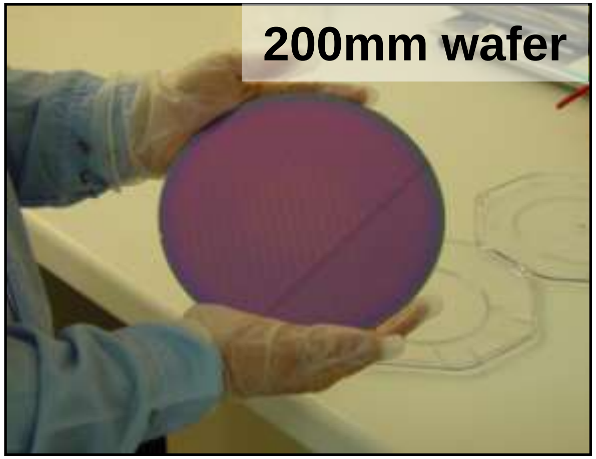
What is heterogeneous integration ?

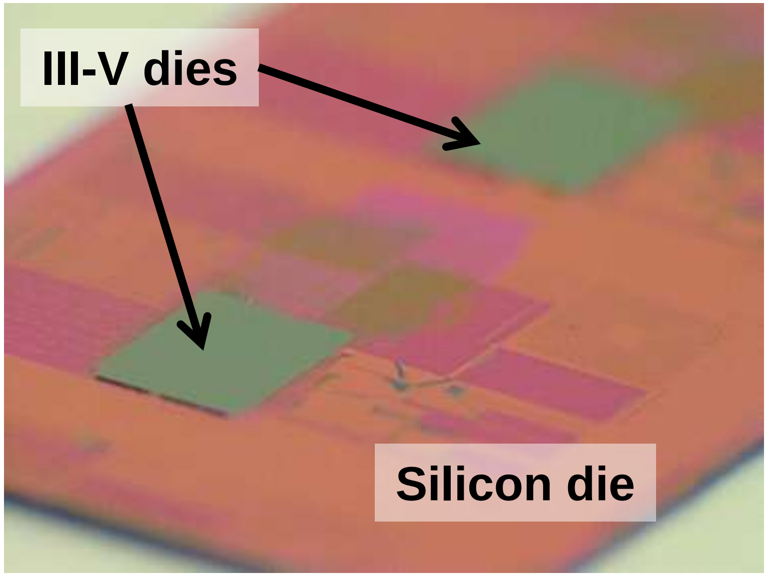


Start:SOI-wafer

Bonding

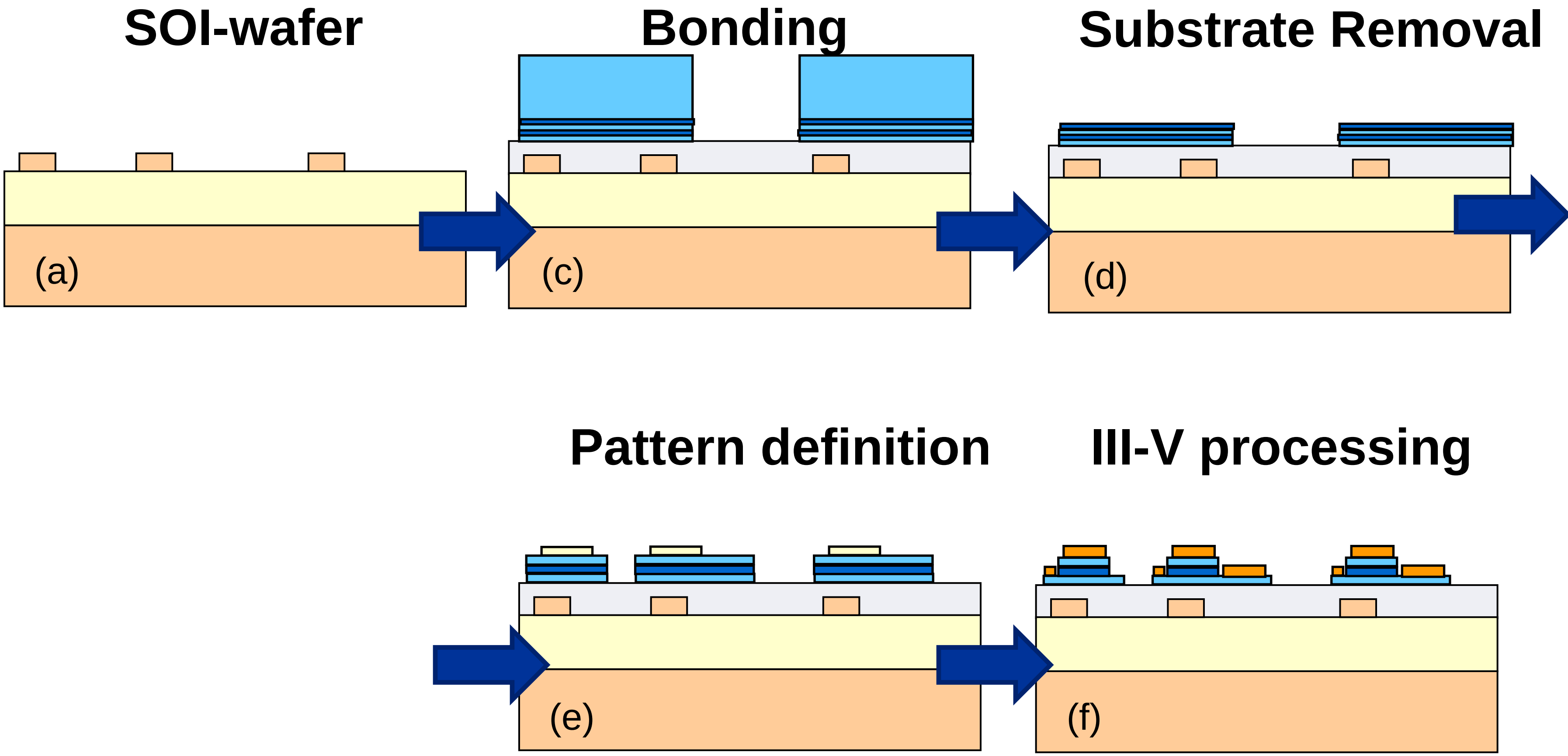
Substrate Removal





What are we talking about ?

What is heterogeneous integration ?



SOI-wafer

Bonding

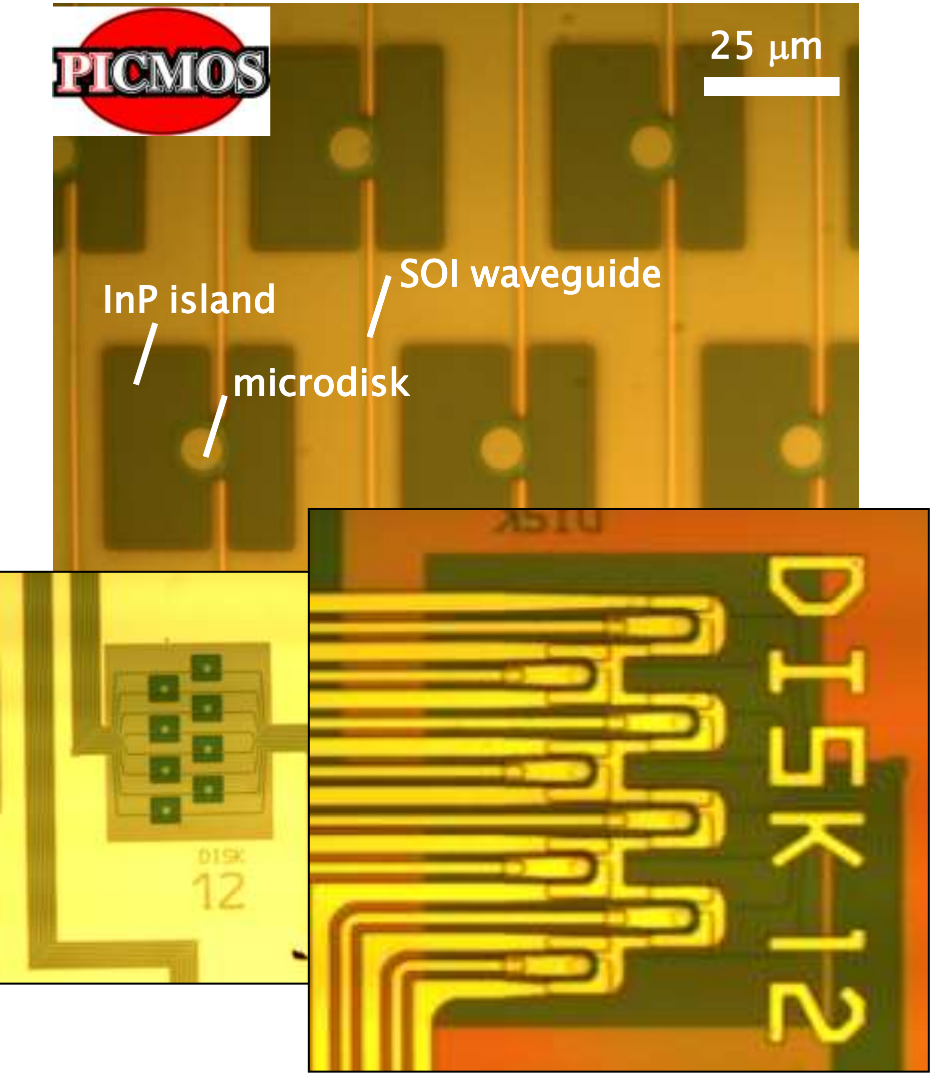
Substrate Removal

Pattern definition

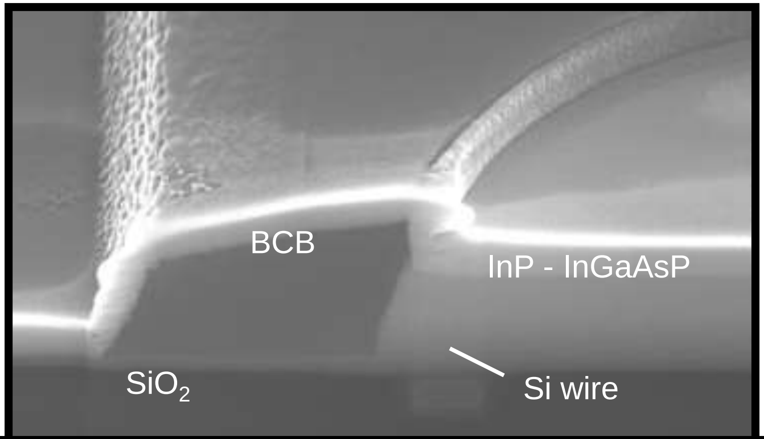
III-V processing

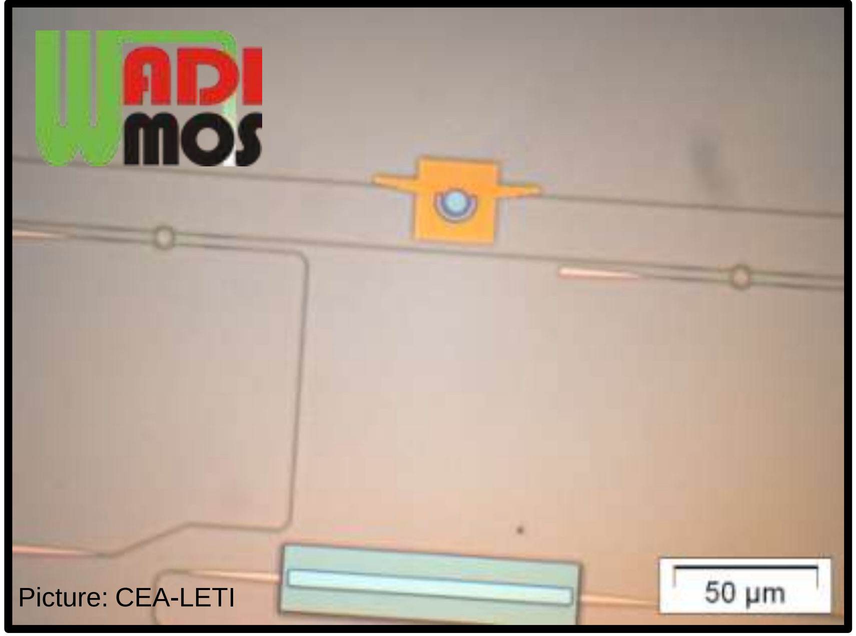
III-V silicon integration

Before metallization



Cross-section





Picture: CEA-LETI

III-V/Silicon photonics

Bonding of III-V epitaxial layers

- Molecular die-to-wafer bonding, direct bonding
  - Based on van der Waals attraction between wafer surfaces
  - Requires “atomic contact” between both surfaces

    - sensitive to **particles, roughness, surface contamination.**

    - well-known materials

LETI, UCSB+INTEL …

- Adhesive die-to-wafer bonding
  - Uses an adhesive layer as a “glue” to stick both surfaces
  - Requirements are more relaxed compared to Molecular

    - glue compensates for particles (some)

    - glue compensates for roughness (all)

    - glue allows (some) contamination of surfaces

    - But: need to qualify polymer

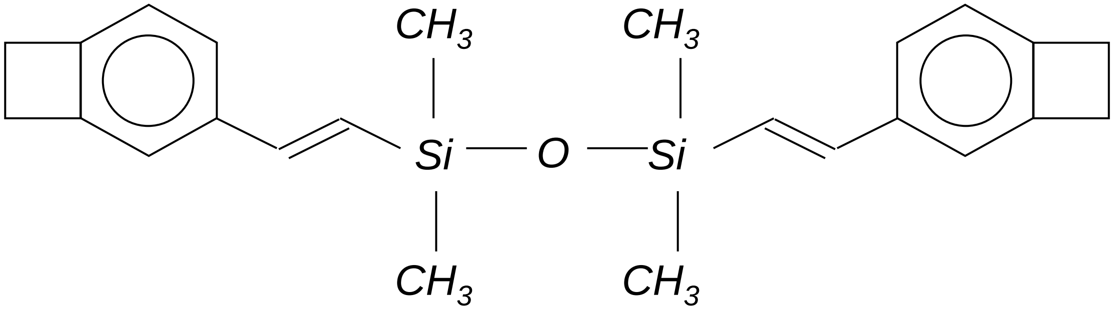
IMEC/Ghent University

Bonding Technology

Requirements for the adhesive for bonding

Optically transparent	<0.1dB/cm
High thermal stability (post-bonding thermal budget)	400C
Low curing temperature (low thermal stress)	250C
No outgassing upon curing (void formation)	OK
Resistant to all kinds of chemicals	$HCl, H_2SO_4, H_2O_2, \ldots$

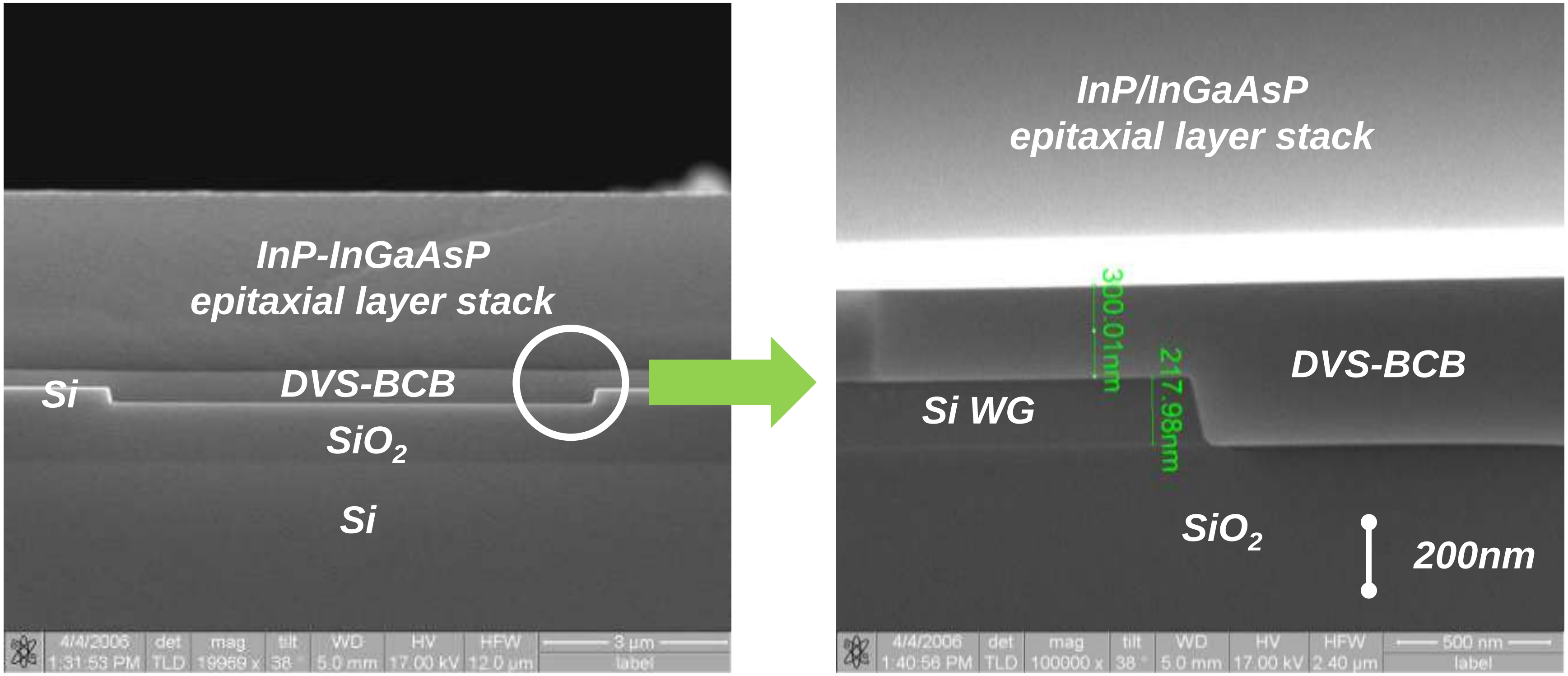
DVS-BCB satisfies these requirements



1,3-divinyl-1,1,3,3-tetramethyldisiloxane-bisbenzocyclobutene

Bonding Technology

Cross-sectional image of III-V/Silicon substrate



- **200nm bonding layer routinely and reliably obtained**
- **Recently : focus on thin bonding layer develoment (<100nm)**

Thin Bonding Layer Process Development

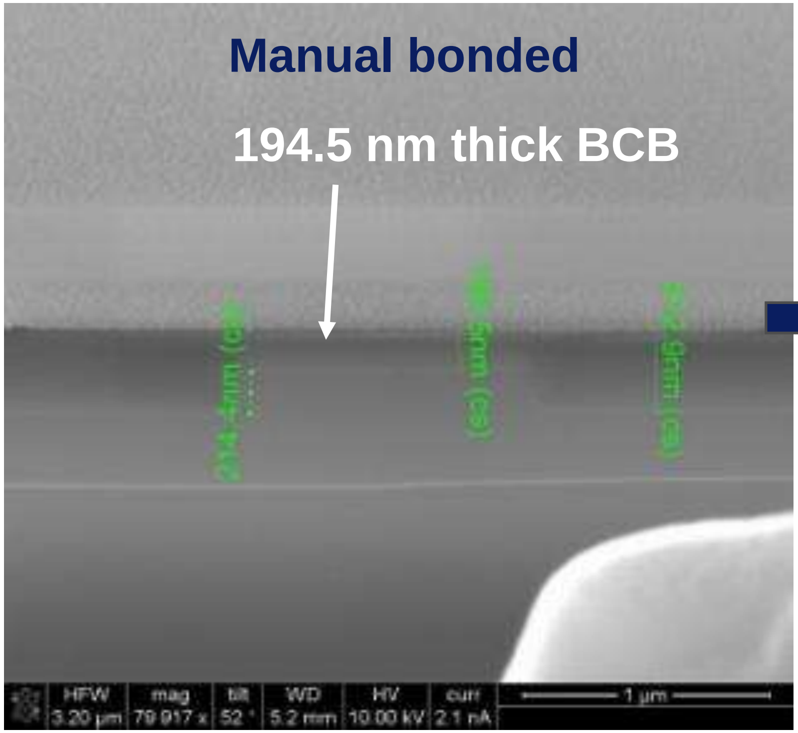
Thin layers needed for:

- Better optical coupling
- Better thermal behaviour

BCB diluted using mesithylene + controlling spin speed

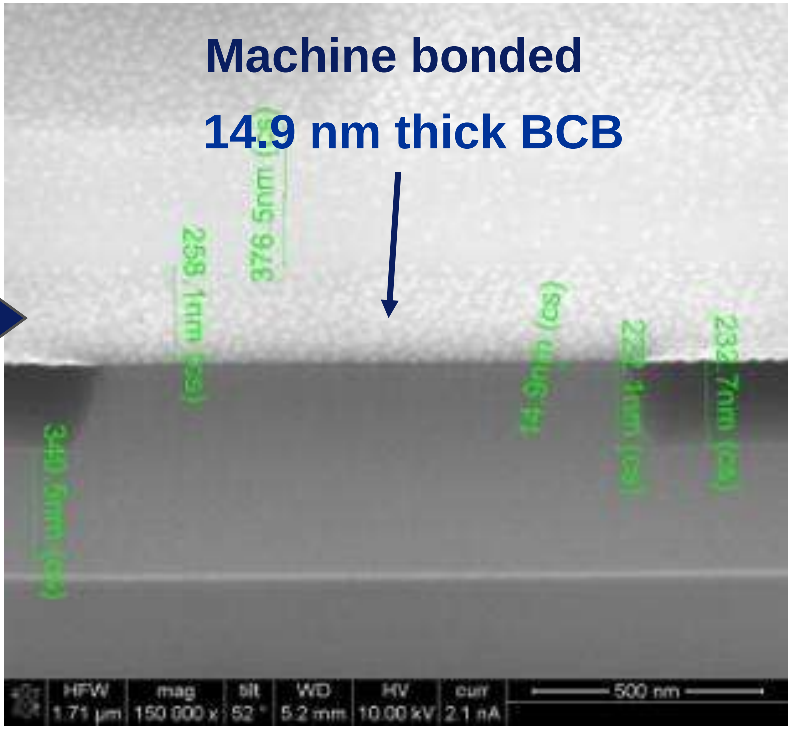
Moved from manual bonding to machine bonding

- Significant improvement in thickness control and uniformity



Manual bonded

194.5 nm thick BCB



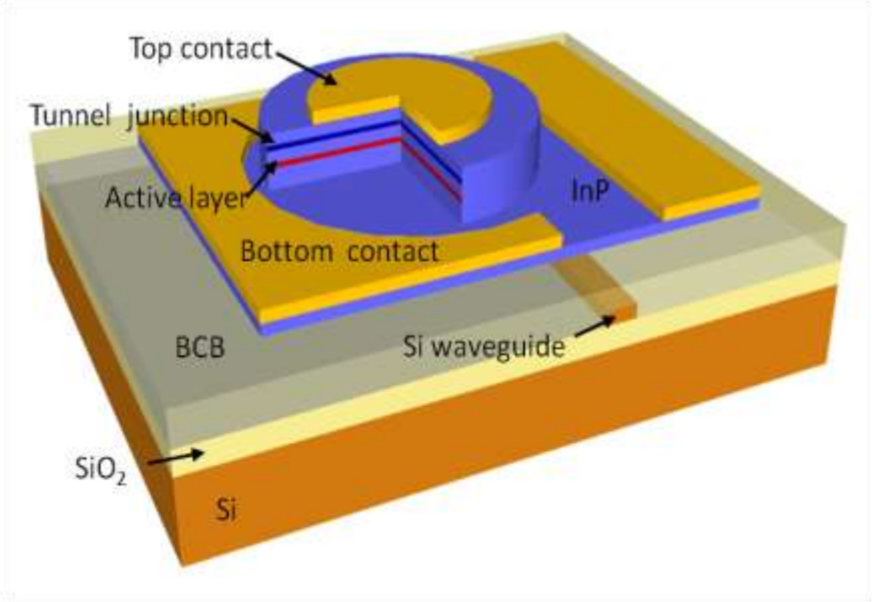
Machine bonded

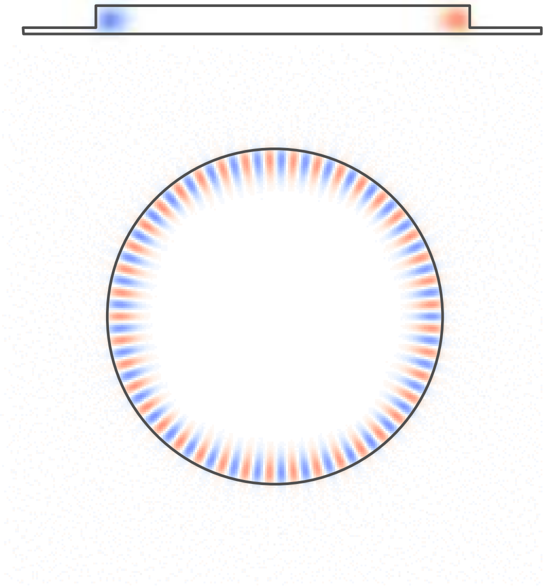
14.9 nm thick BCB

Integrated microdisk laser

Microdisk laser

- III-V semiconductor disk on top of silicon waveguide

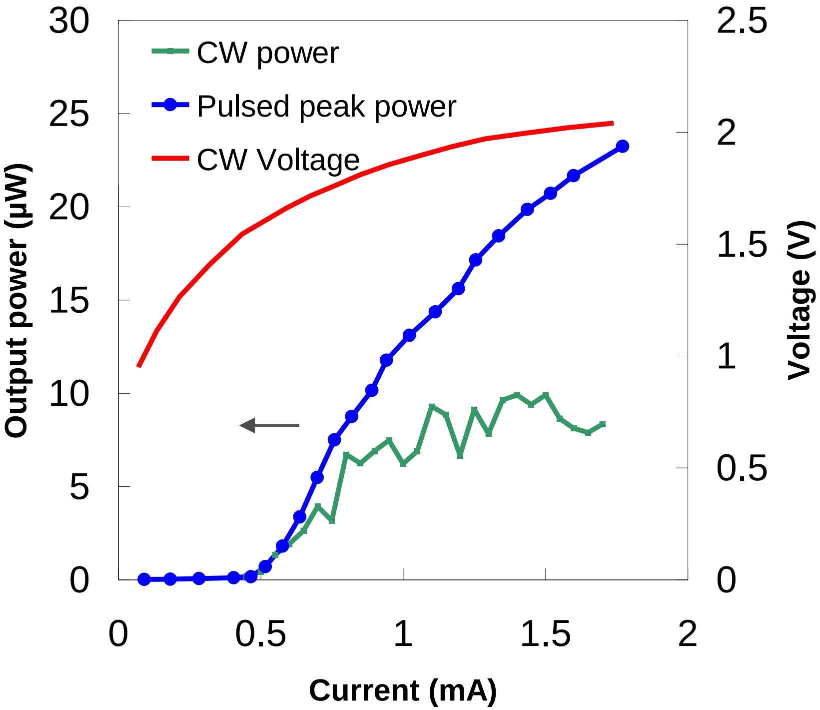


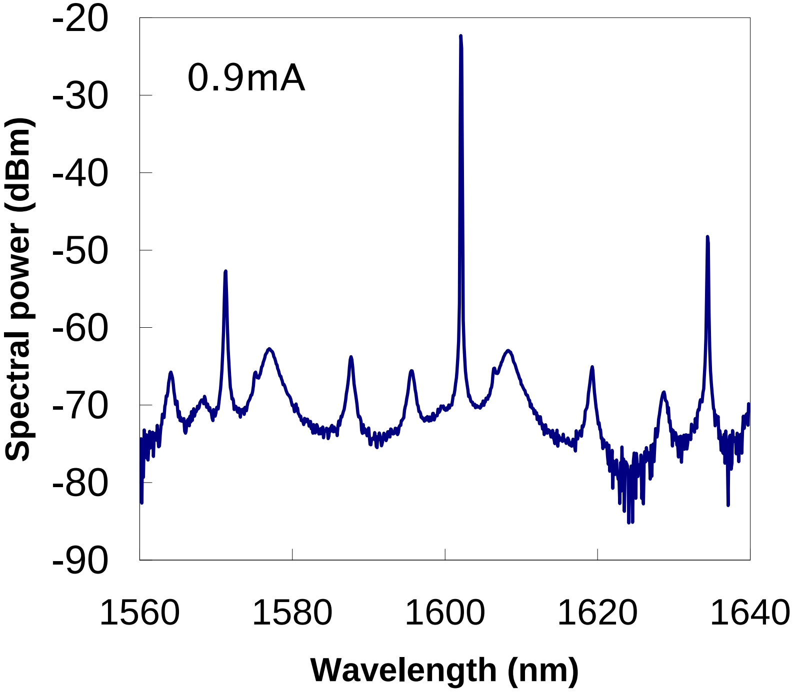


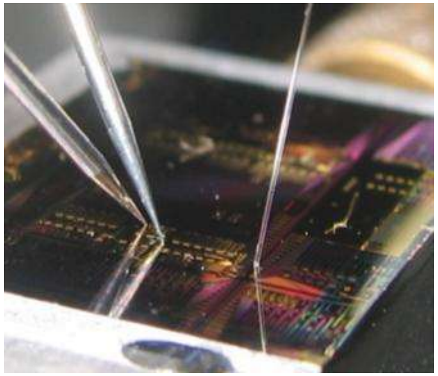
- Supports whispering gallery modes circulating around edge
- 7.5µm diameter ➔ low footprint
- 150µA threshold current ➔ low power consumption

Continuous-wave lasing

1-µm thick, 7.5-µm devices exhibit continuous-wave lasing







Threshold current I_{th} = 0.5mA, voltage V_{th} = 1.5-1.7V

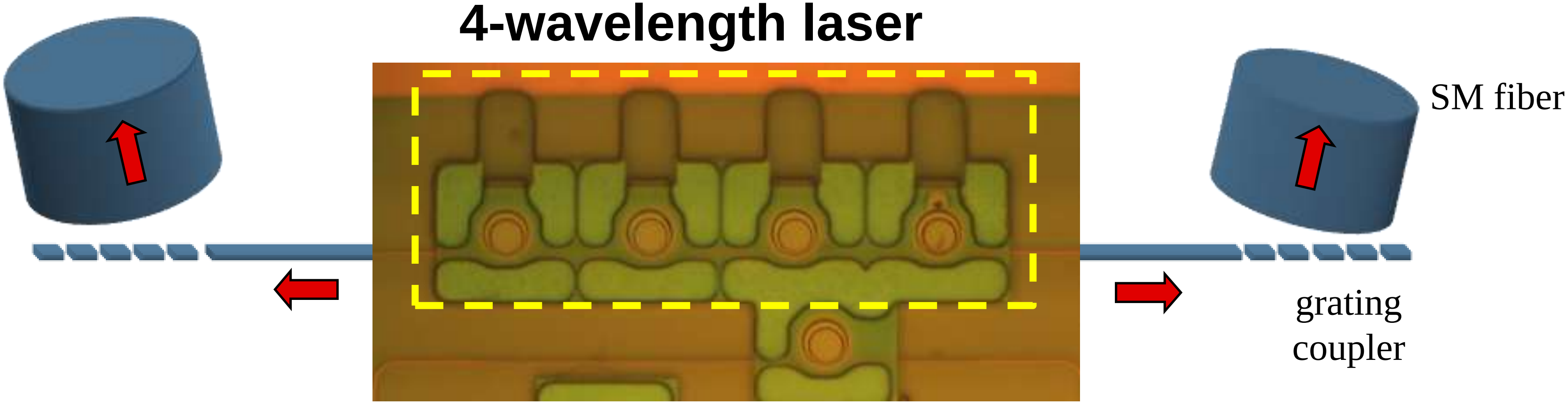
slope efficiency = 30µW/mA, up to 10µW

(Pulsed regime: up to 100µW peak power)

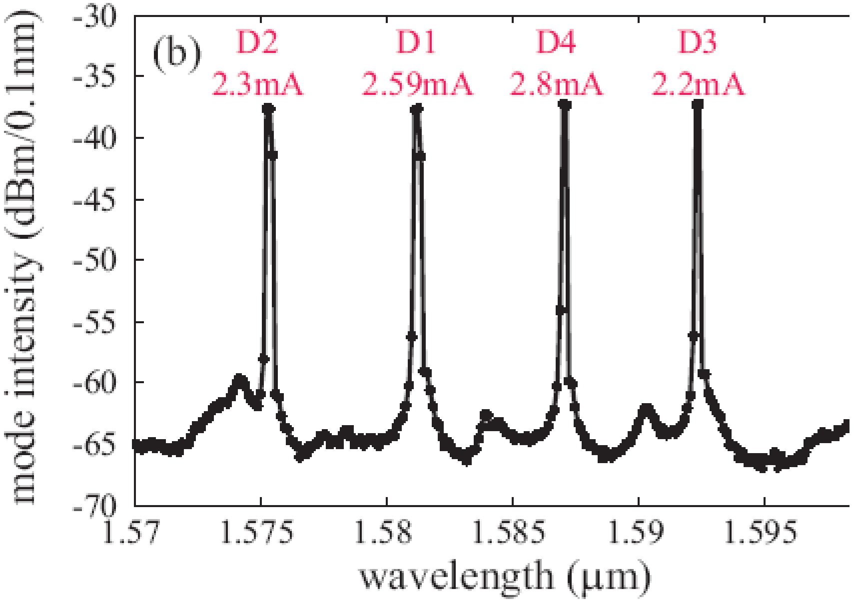
J. Van Campenhout et al., *"Electrically pumped inp-based microdisk lasers integrated with a nanophotonic silicon-on-insulator waveguide circuit"* Optics Express, May 2007

Multi-wavelength Laser

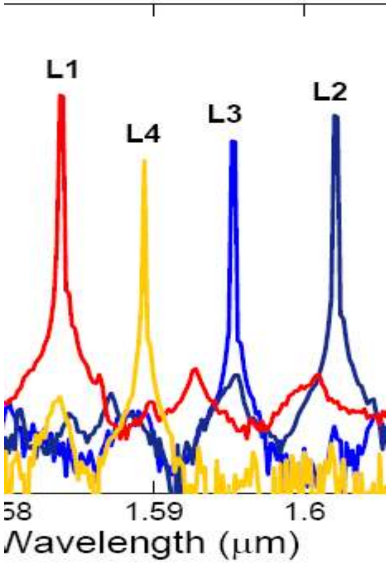
4-wavelength laser



All pumped simultaneously

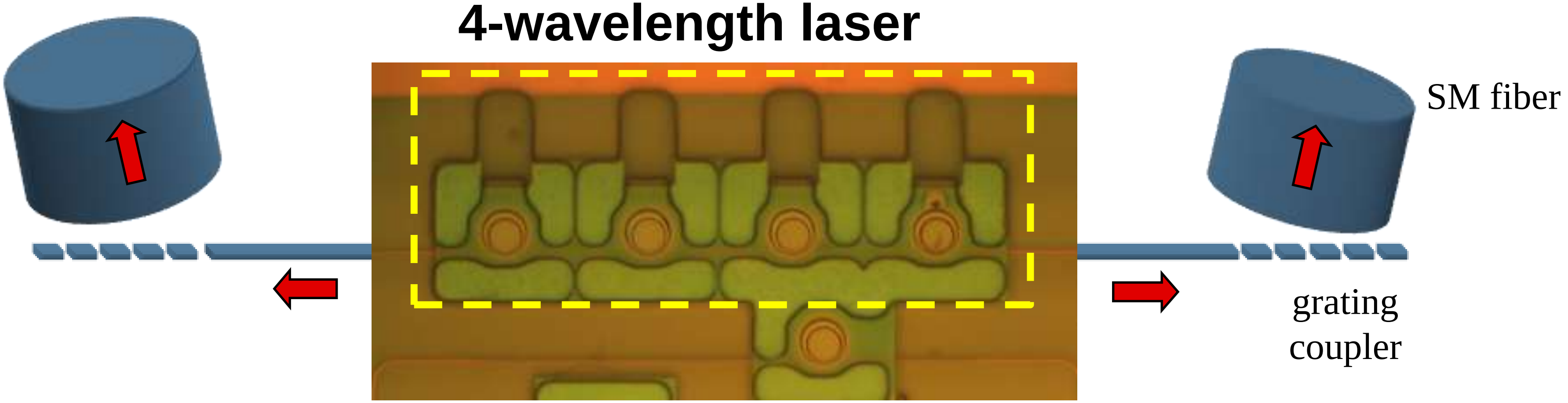


All pumped individually



Multi-wavelength Laser

4-wavelength laser

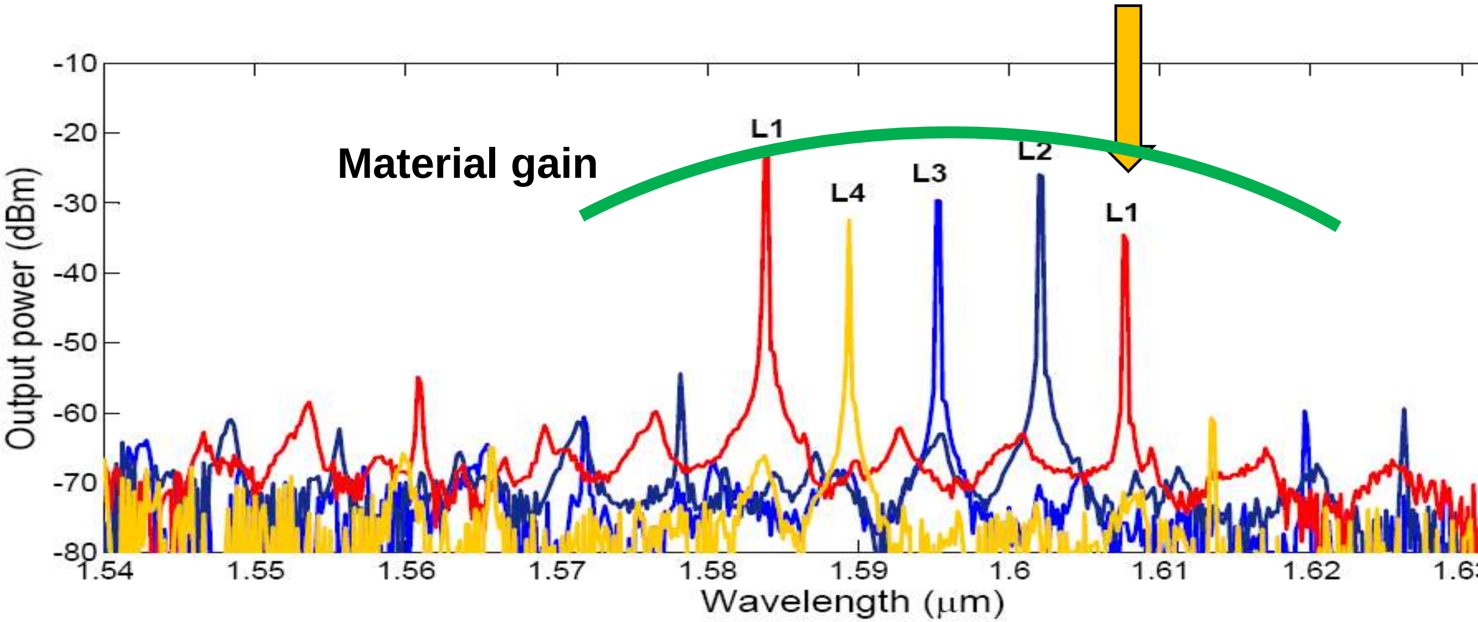


SM fiber

grating coupler

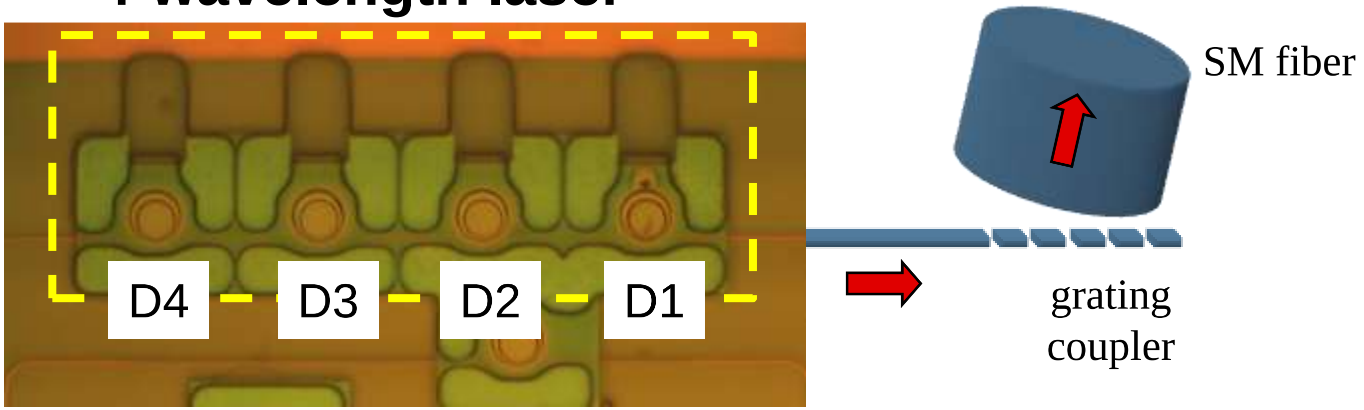
Low SMSR

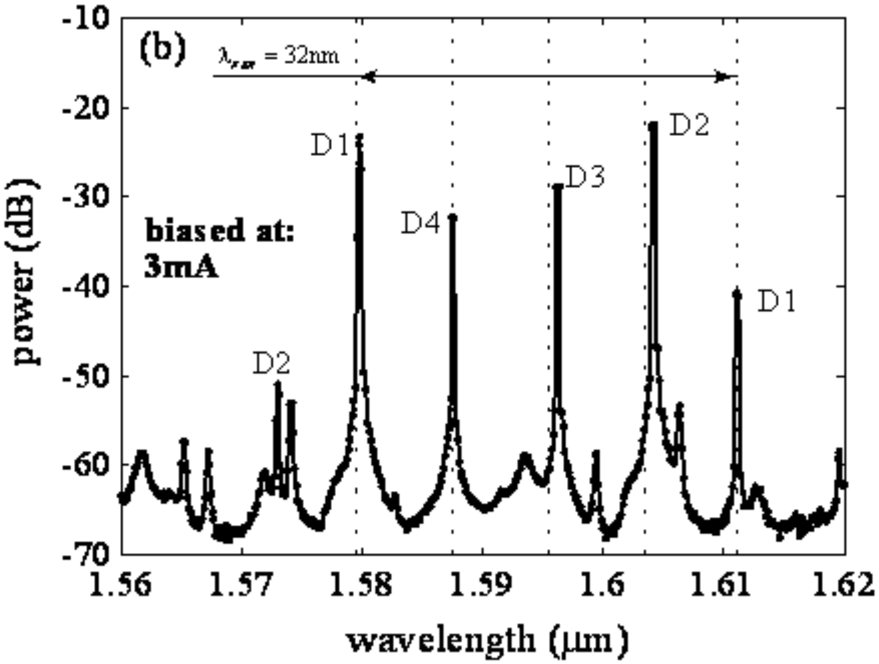
Material gain



Multi-wavelength Laser

4-wavelength laser



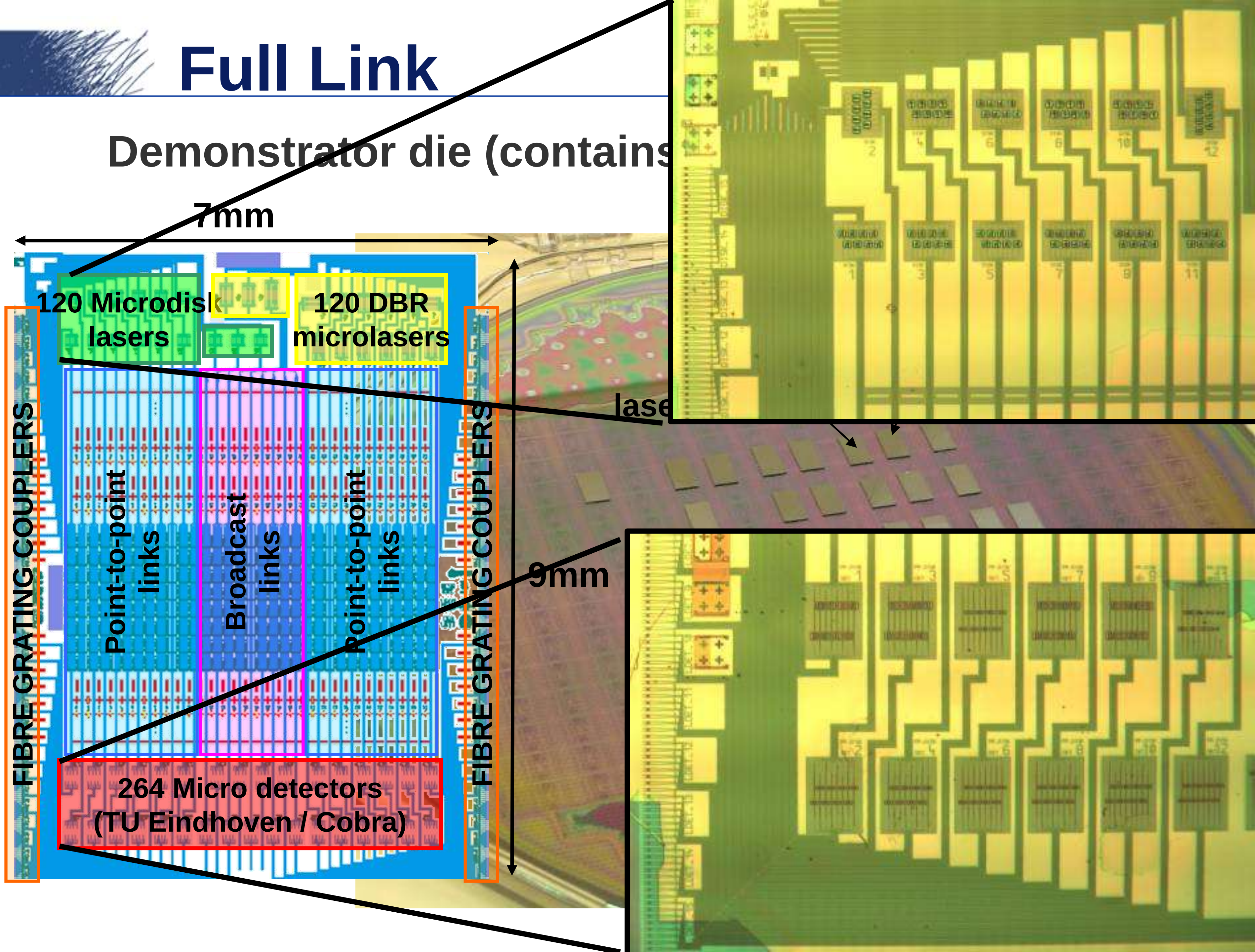


Uneven power levels

- Lower power in channels crossing other disks
- Coupling to higher order modes in next disks
- Need thinner disks

Full Link

Demonstrator die (contains



Microdisk lasers

Targets in our new project (WADIMOS)

- Demonstrate improved device performance
  - Lower threshold power
  - Higher output power
  - More stable operation
- Demonstrate fabrication in CMOS pilot line
  - On 200mm line
  - Using CMOS tools
  - Using single epitaxial structure for source and detector
- Look at novel applications
  - Operation as wavelength convertor
  - Operation as all-optical flip-flop

Thermal resistance

Microdisk is almost completely surrounded by BCB

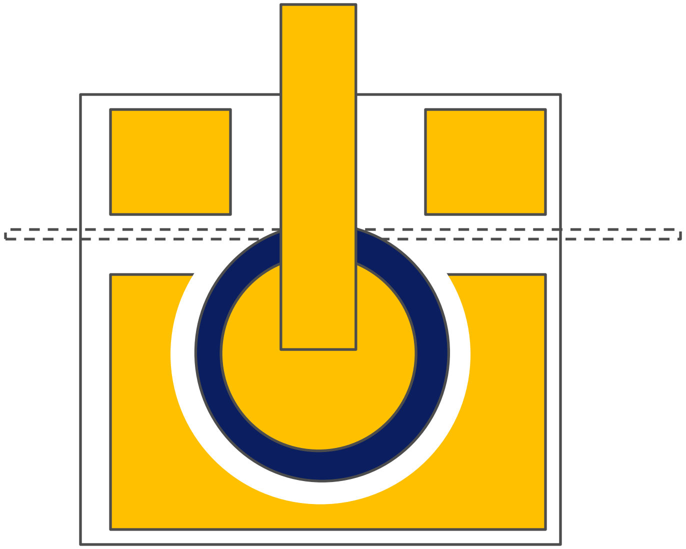
- Thermal conductivity BCB ≈ 0.3 $Wm^{-1}K^{-1}$

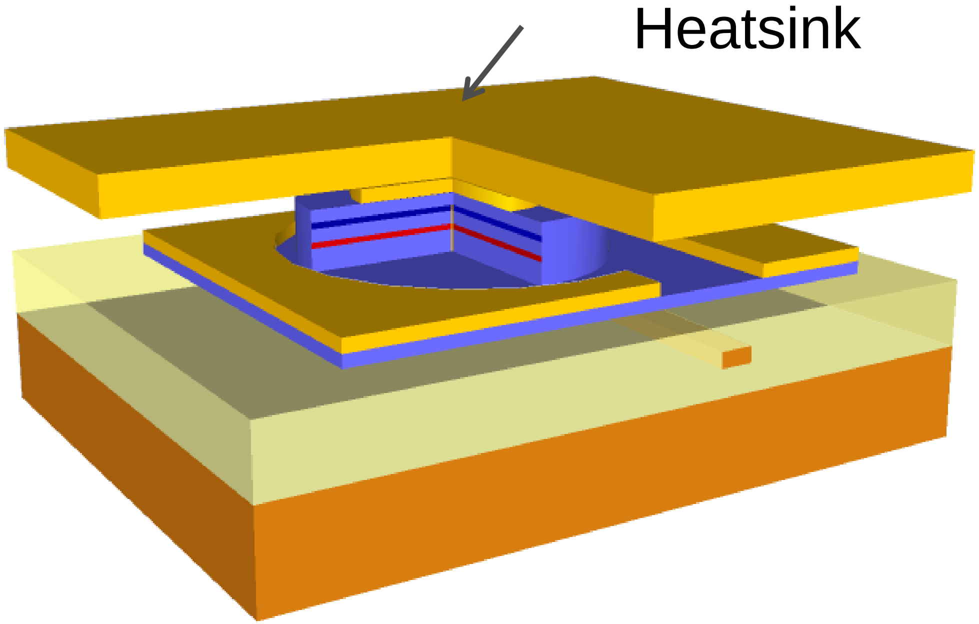
Heat is confined in disk structure

- Self heating gives rise to thermal roll-over

Extract heat from disk by using a thermal heat sink

Thick layer (600nm) of gold on top of the disk





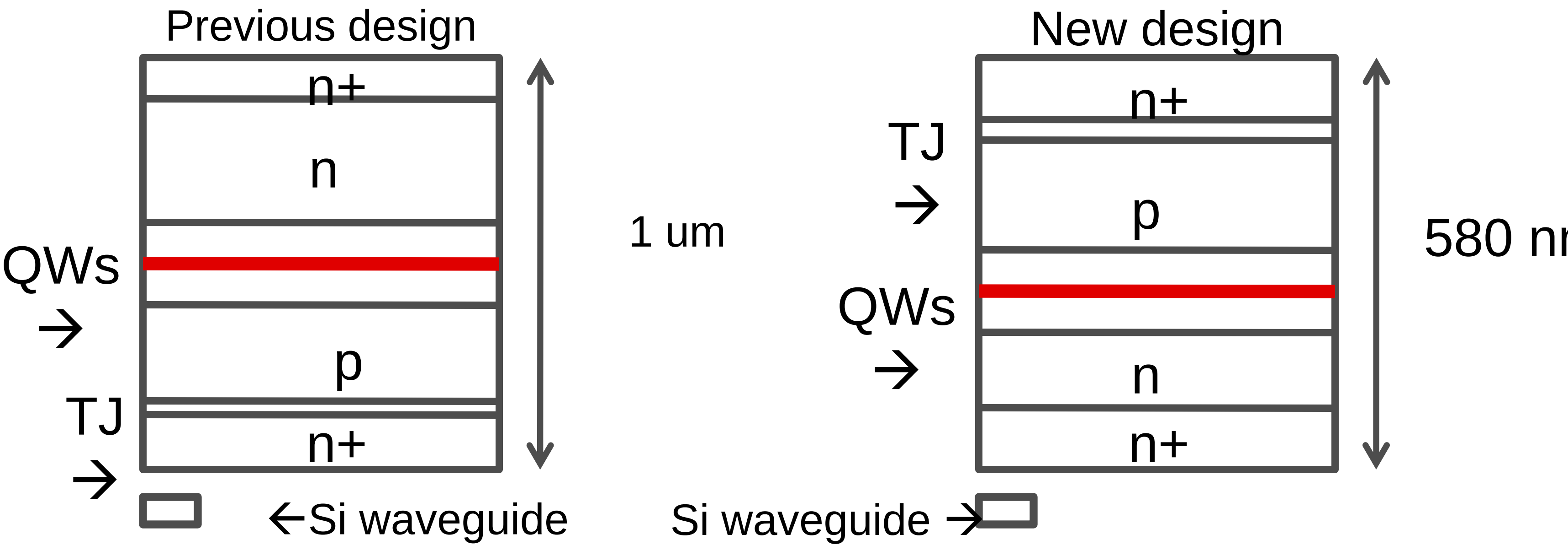
Tunnel junction

Thin degenerately doped p-n junction

- Fermi-levels within valence and conduction band

Reverse biased tunnel junction

- Electrons can tunnel from p-type layer to n-type layer
- Only thin (+/- 20 nm) heavily doped p-type layer required
- Eliminate DBBA by using TJ material with $E_G > E_{G\ \text{laserdiode}}$



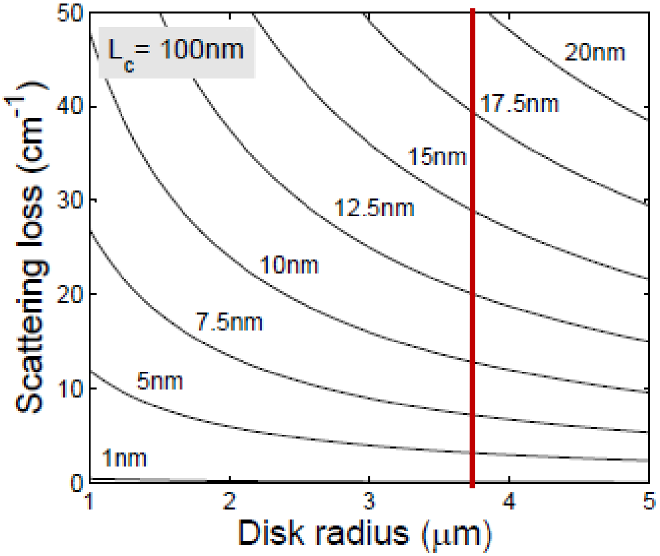
Scattering loss

Sidewall roughness induces scattering loss

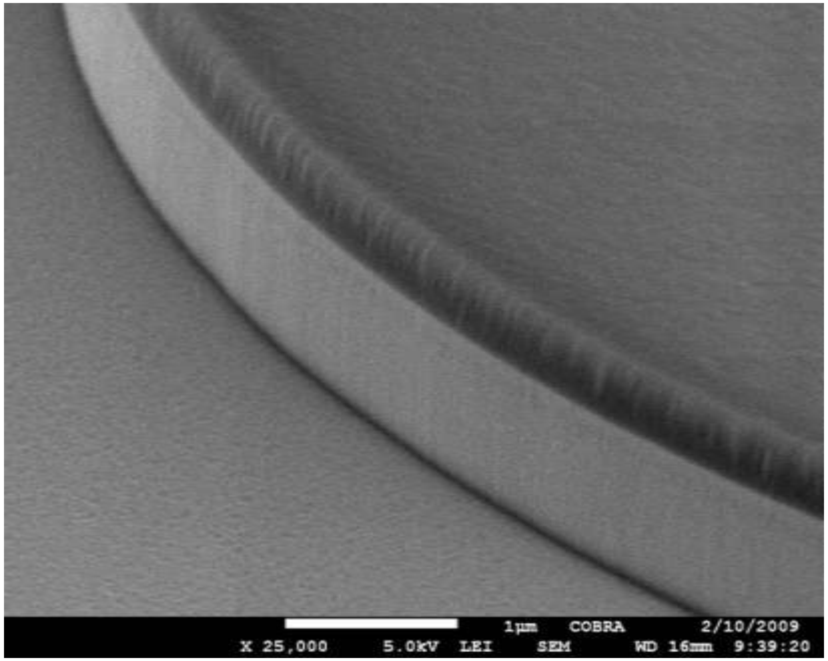
- Estimation of roughness of previous devices (1um thick)
  - $\sigma \approx 10 - 20$ nm
  - $L_c \approx 100$ nm

Scattering loss scales linearly with thickness

- New epitaxial structure 580 nm thick



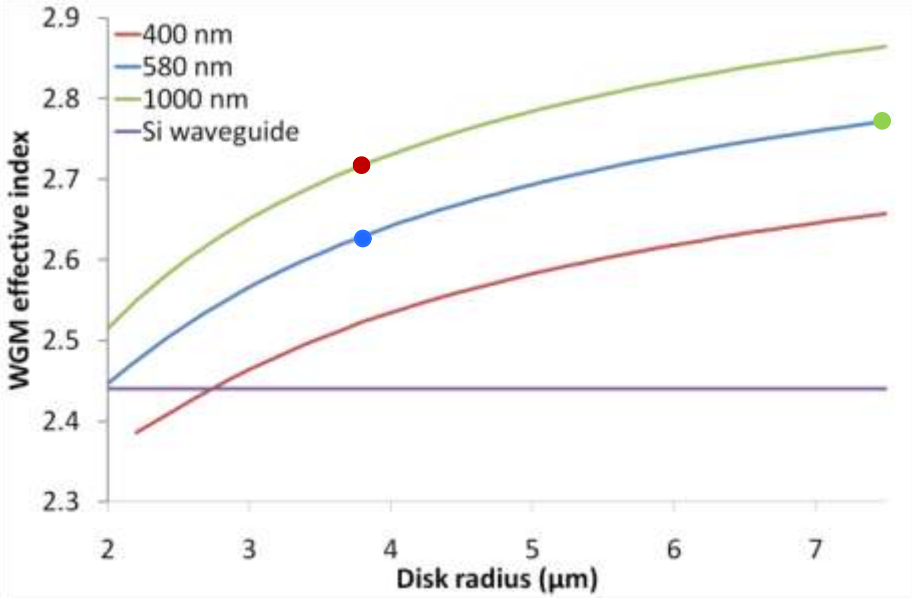
[J.E. Heebner, et al, Opt. Expr. 15(8), 2007]

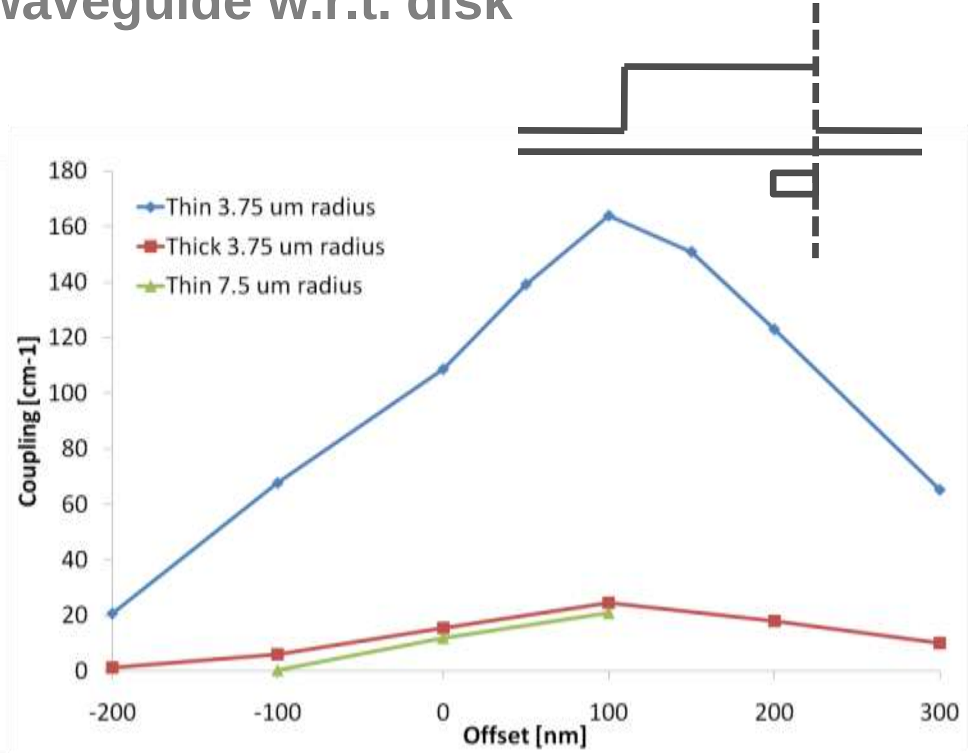


Coupling efficiency

Evanscent coupling to underlying waveguide

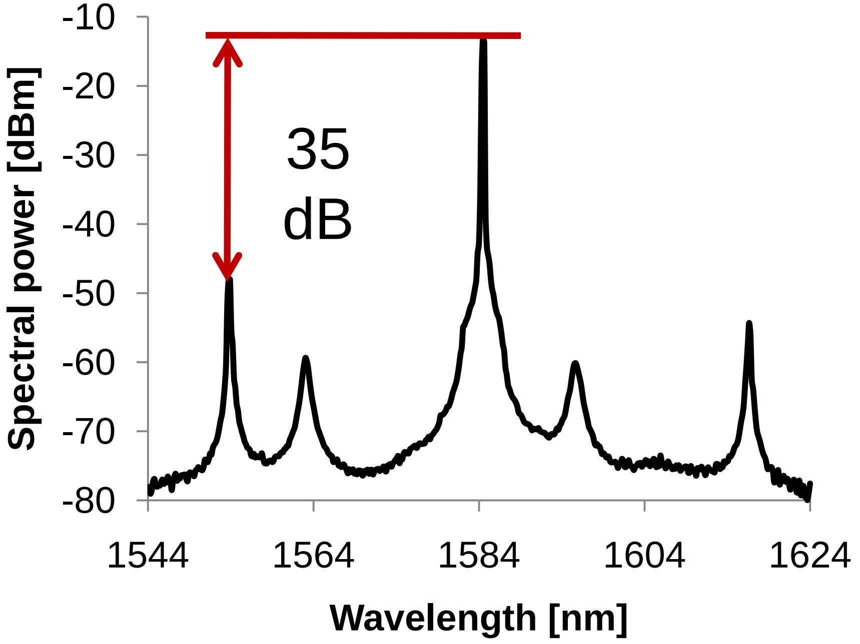
- Phase match between disk and waveguide
  - minimize disk height and radius
- Relaxes constraint on bonding layer thickness
- Optimize coupling length
  - Lateral offset of the waveguide w.r.t. disk

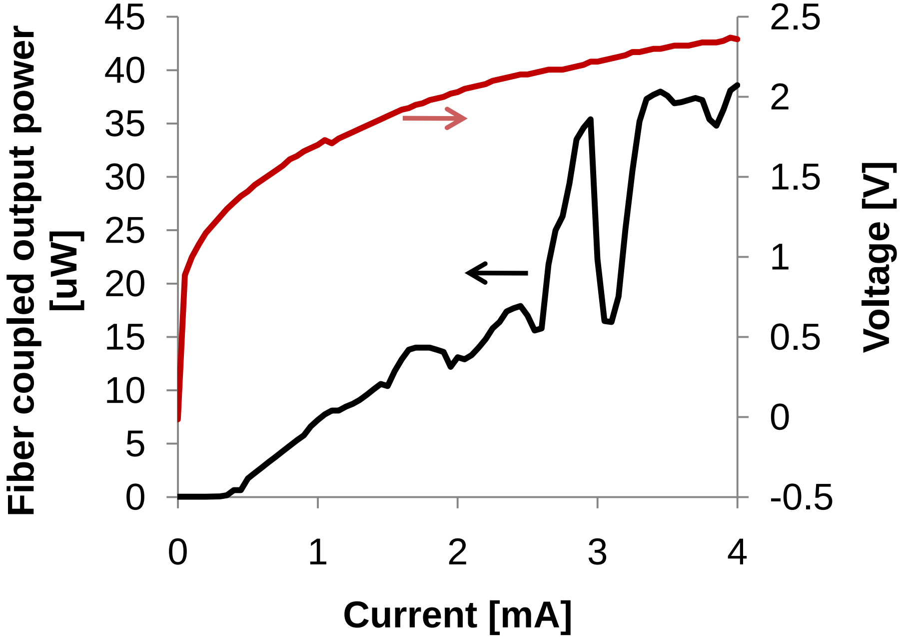




Improved devices

New generation devices (Group IV 2009)





- Threshold current **350 uA**
- Output power 120 uW (CW)
- SMSR = 35 dB

7.5 um disk diameter

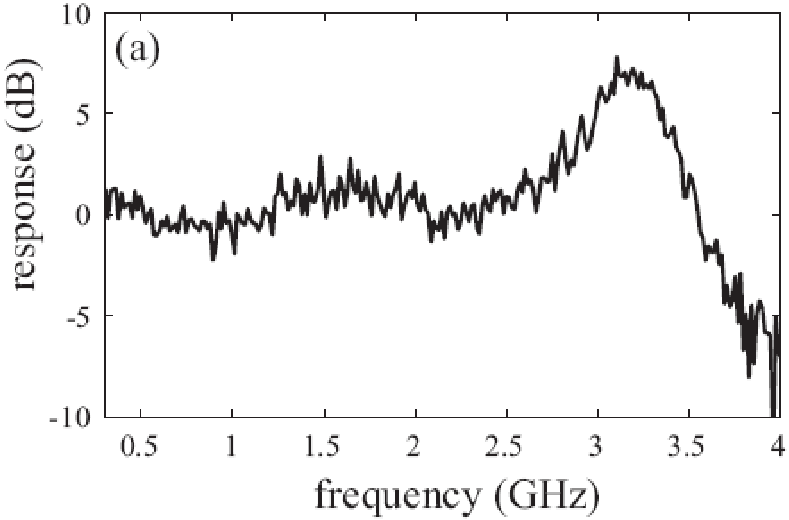
- Best devices: down to **150uA** threshold current !!!)

Direct modulation

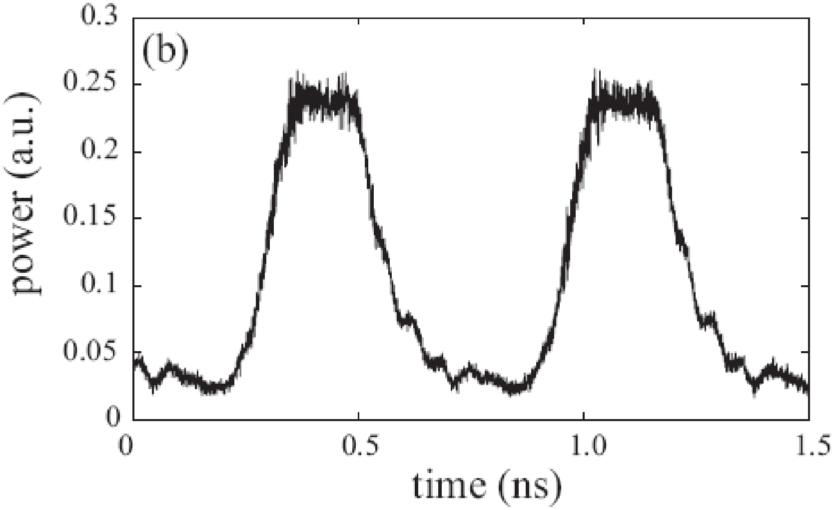
Direct modulation critical for practical application

- 10GHz expected within reach from simulations
- “Double carrier reservoir” may limit speed however
  - (Measurments complicated by wavelength (L-band) and low power)

Small signal response

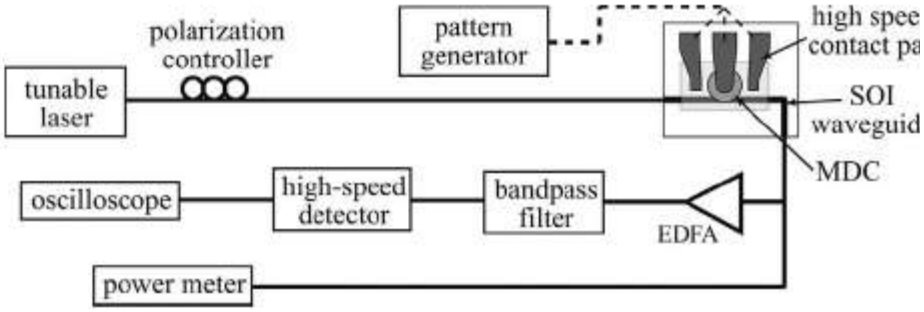


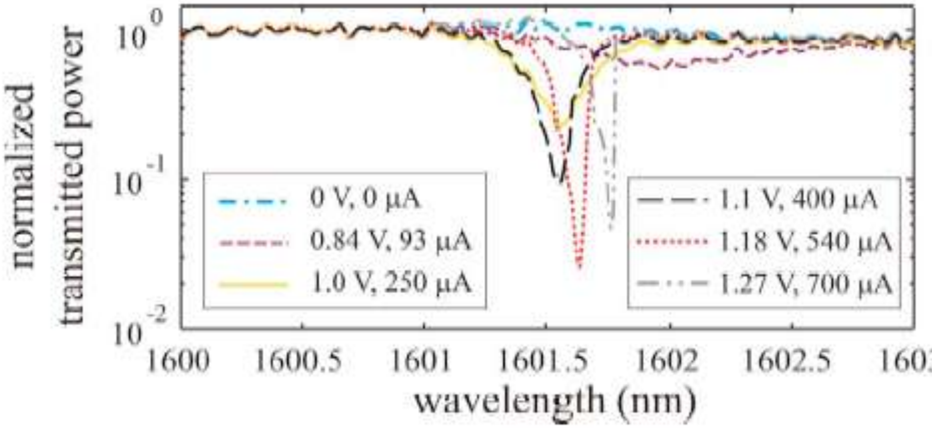
1.5GHz square wave form

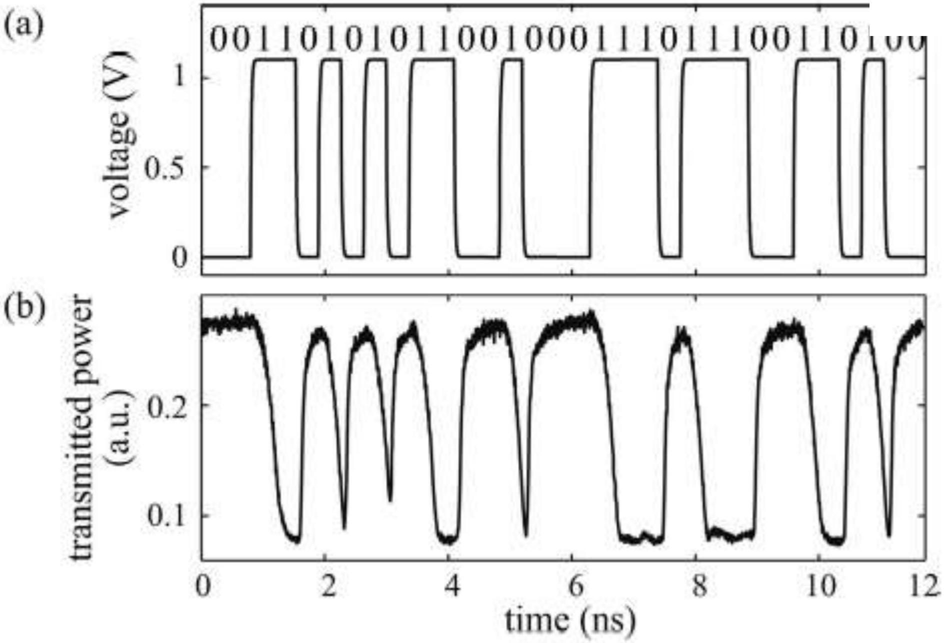


Modulation

Micro-disk used as external modulator







2.73 Gb/s data modulation

Microdisk lasers

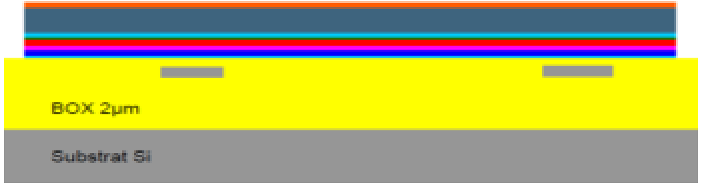
Targets in our new project (WADIMOS)

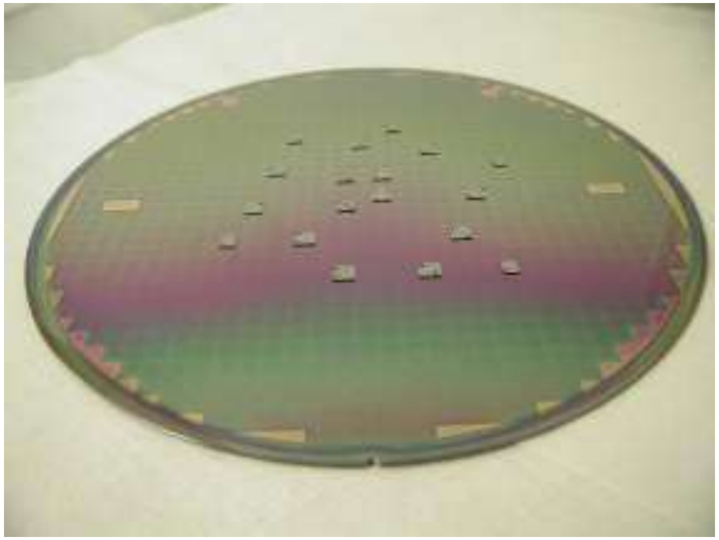
- Demonstrate improved device performance
  - Lower threshold power
  - Higher output power
  - More stable operation
- Demonstrate fabrication in CMOS pilot line
  - On 200mm wafers
  - Using CMOS tools
  - Using single epitaxial structure for source and detector
- Look at novel applications
  - Operation as all-optical flip-flop

CMOS compatible fabrication

Fabrication

- Bonding of III-V dies



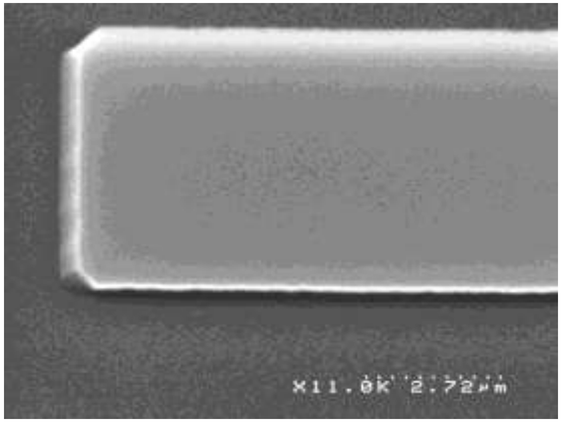


(fabrication by CEA-LETI)

CMOS compatible fabrication

Fabrication

- Etching of detector mesa

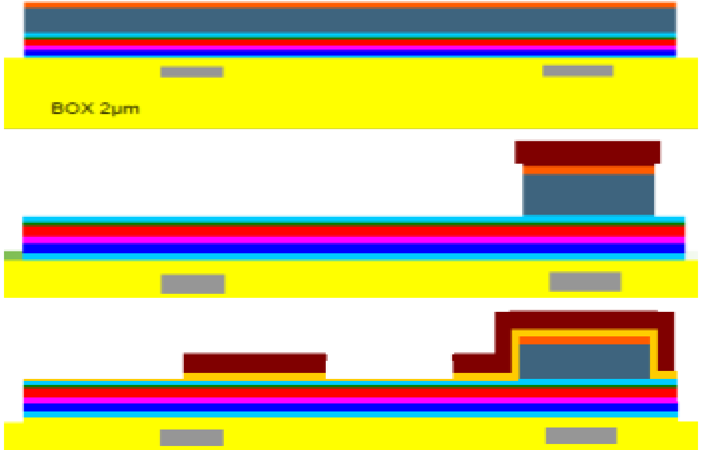


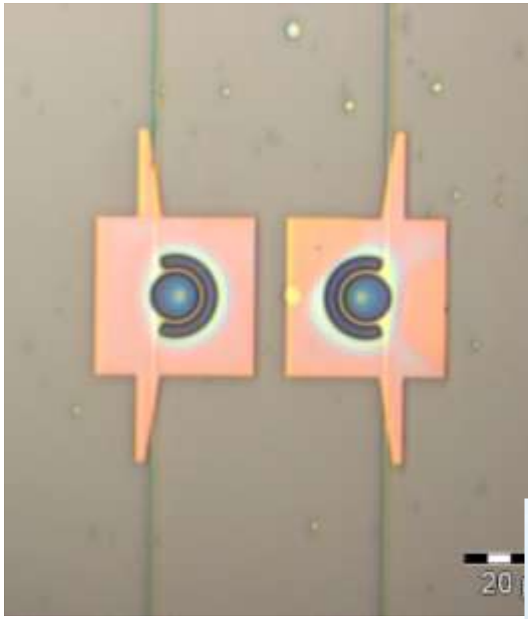
(fabrication by CEA-LETI)

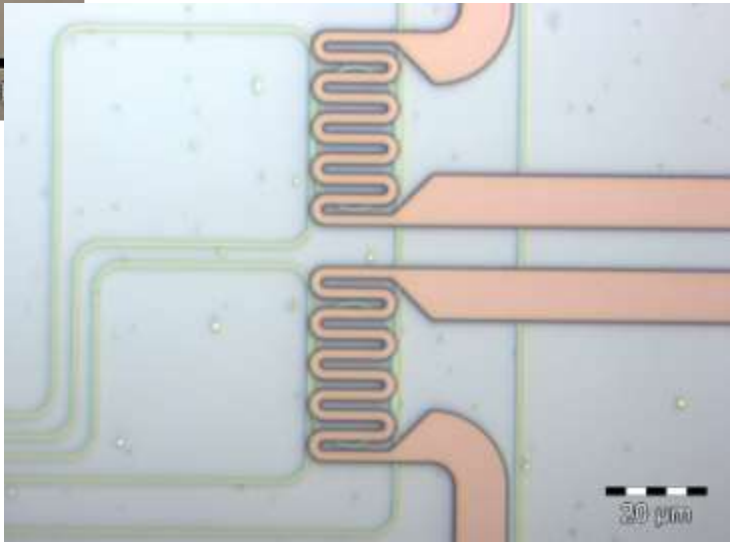
CMOS compatible fabrication

Fabrication

- Etching of disk mesa





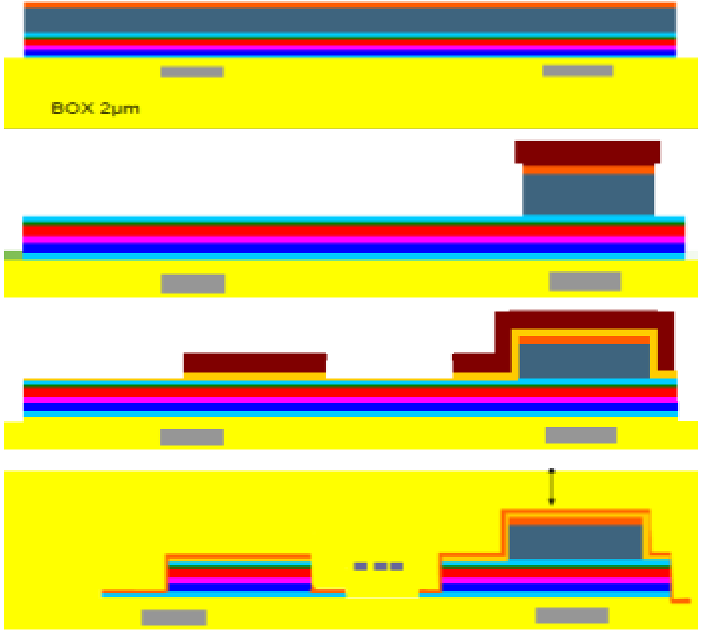


(fabrication by CEA-LETI)

CMOS compatible fabrication

Fabrication

- **Planarization**

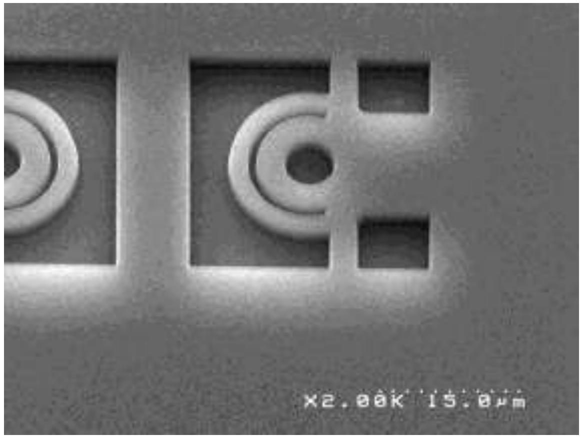


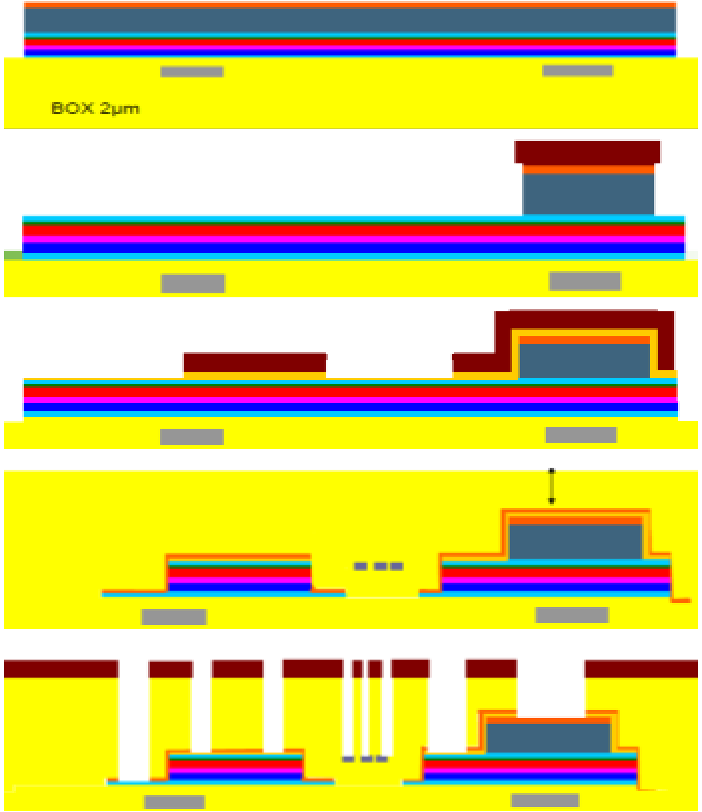
(fabrication by CEA-LETI)

CMOS compatible fabrication

Fabrication

- Contact opening



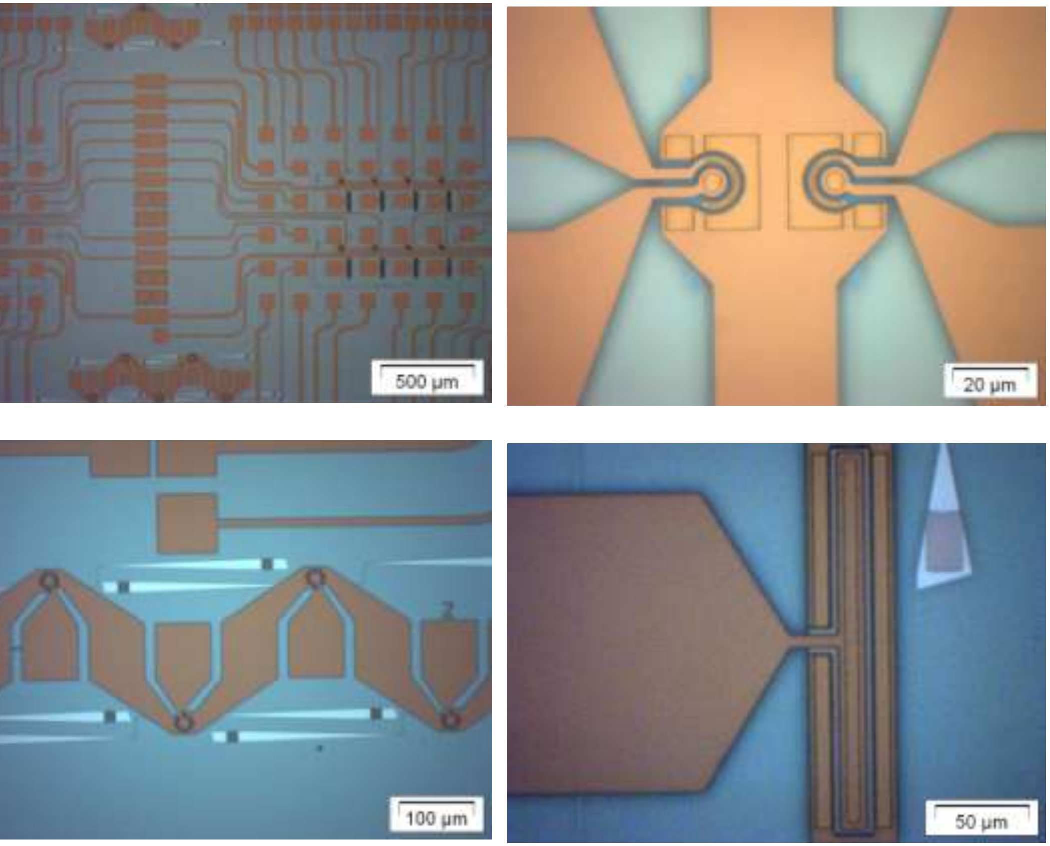


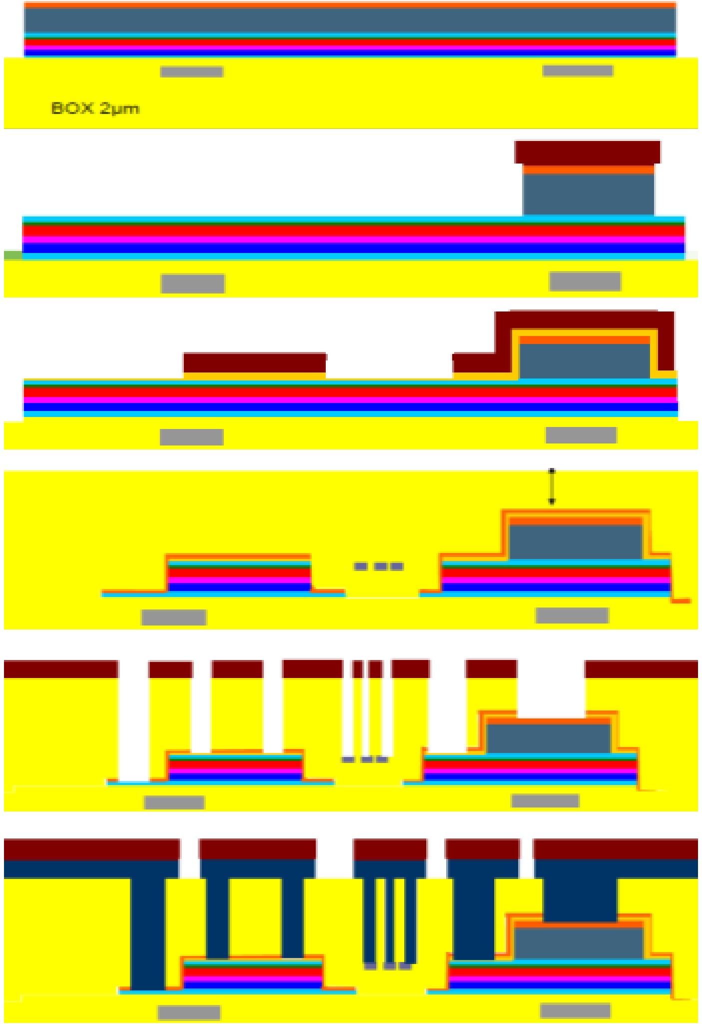
(fabrication by CEA-LETI)

CMOS compatible fabrication

Fabrication

- CMOS compatible contacts (Ti/TiNi)





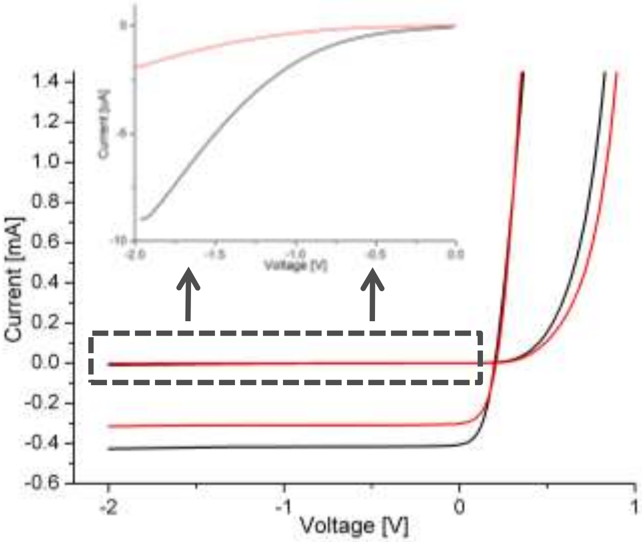
(fabrication by CEA-LETI)

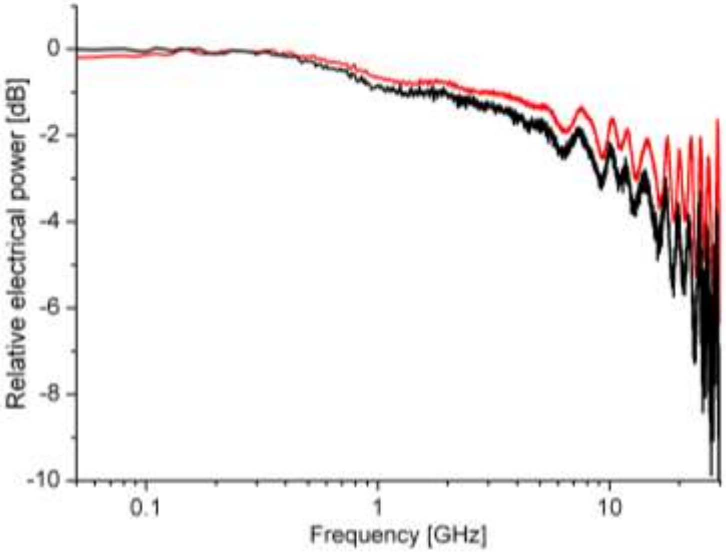
Preliminary charachterisation

Detectors

- Responsivity: 0.7-0.9 A/W
- Dark current: 1-10 uA
- Resistance around 100 Ohm

- ~ 10 GHz for 80 um long detector @ -1.5 V
- ~ 15 GHz for 20 um long detector @ -1.5 V
- Ripple → Calibration?

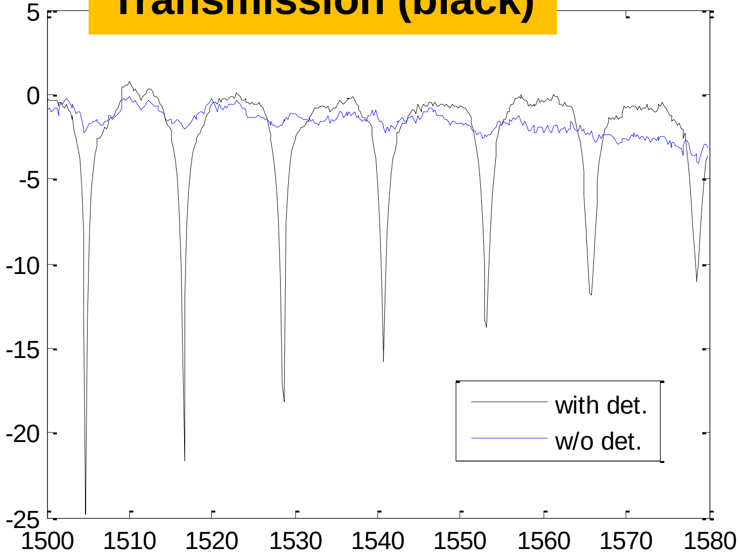


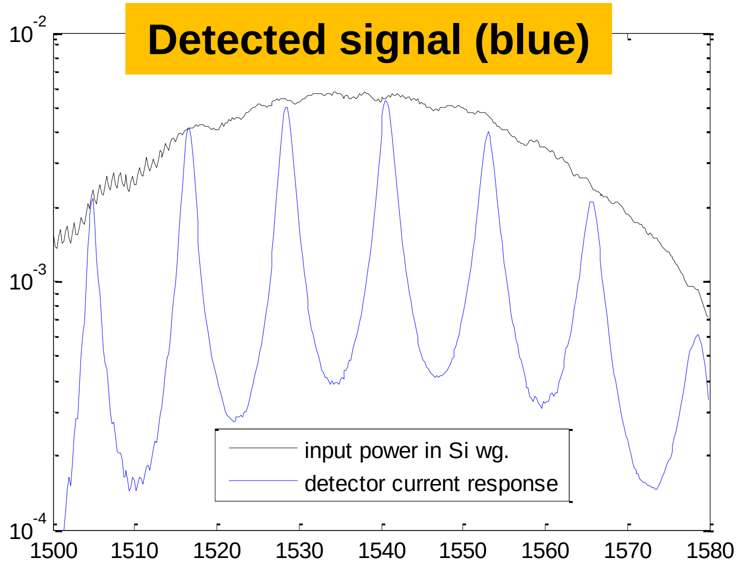


Resonant detectors

Resonant detectors

- MSM-detector integrated on ring-resonator
- 2um device is sufficient
- Potentially very low capacitance


Transmission (black)

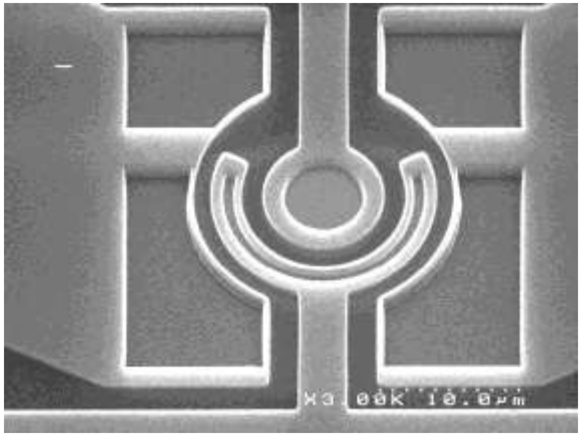

Detected signal (blue)

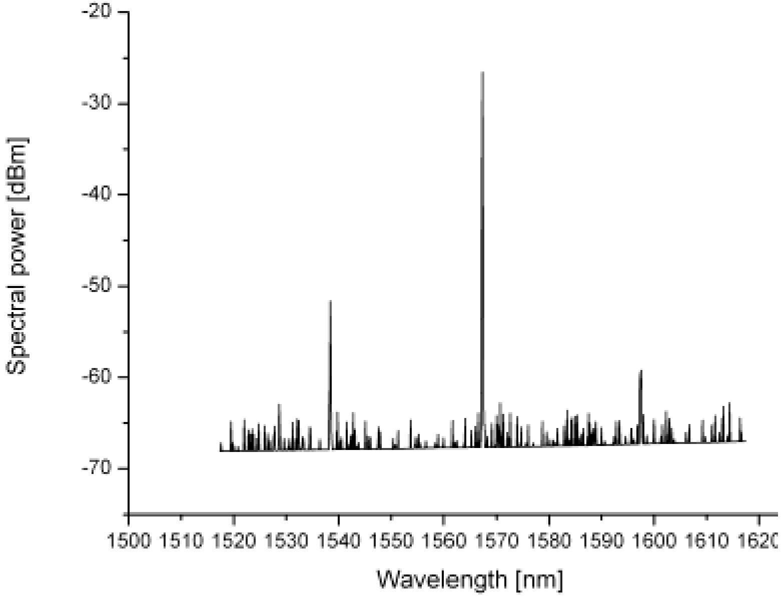

Resonant detector on ring

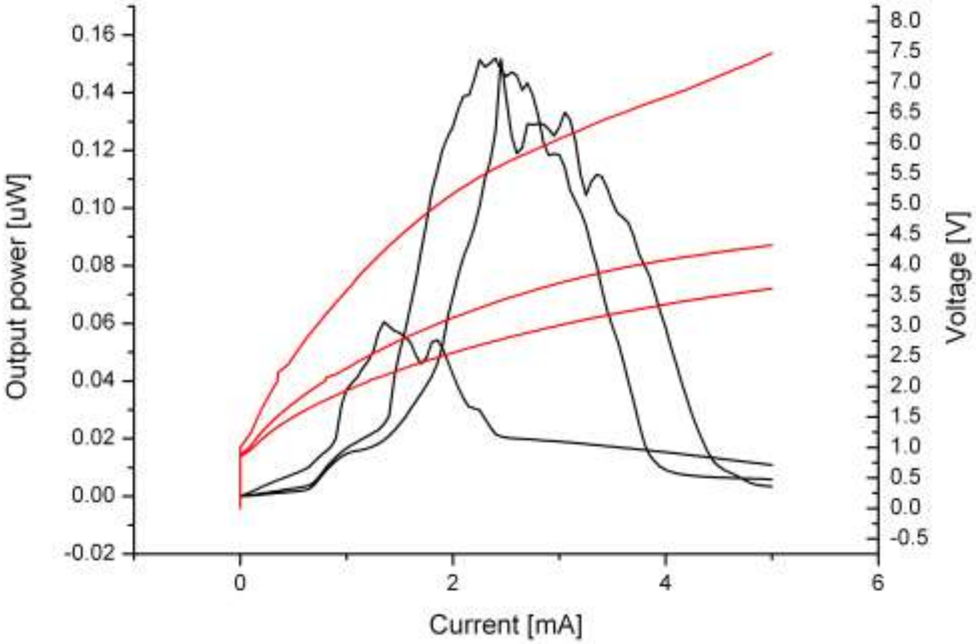
Preliminary charachterisation

Lasers

- **First demonstration of microdisk lasers fabricated in CMOS environment**
- **Threshold current 0.8mA (expected from design)**





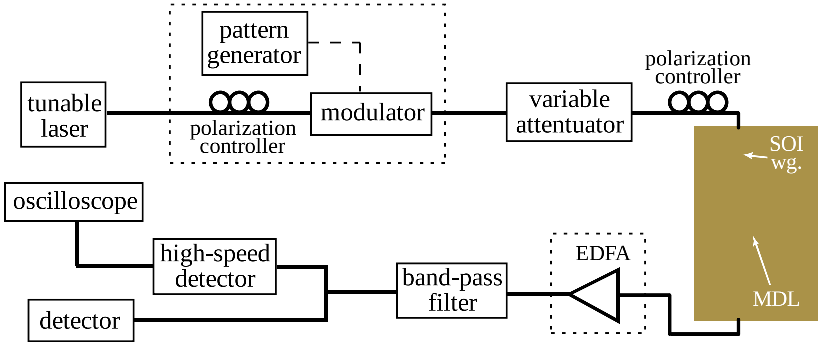


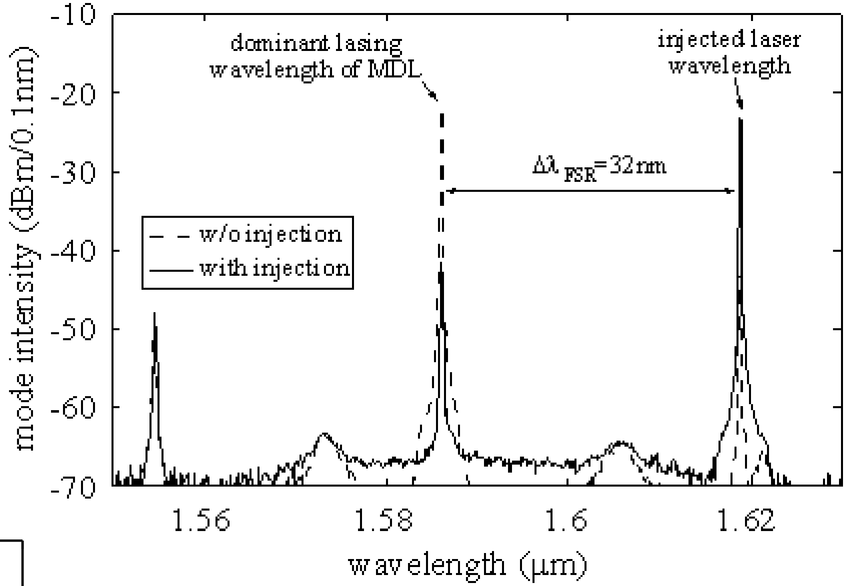
Microdisk lasers

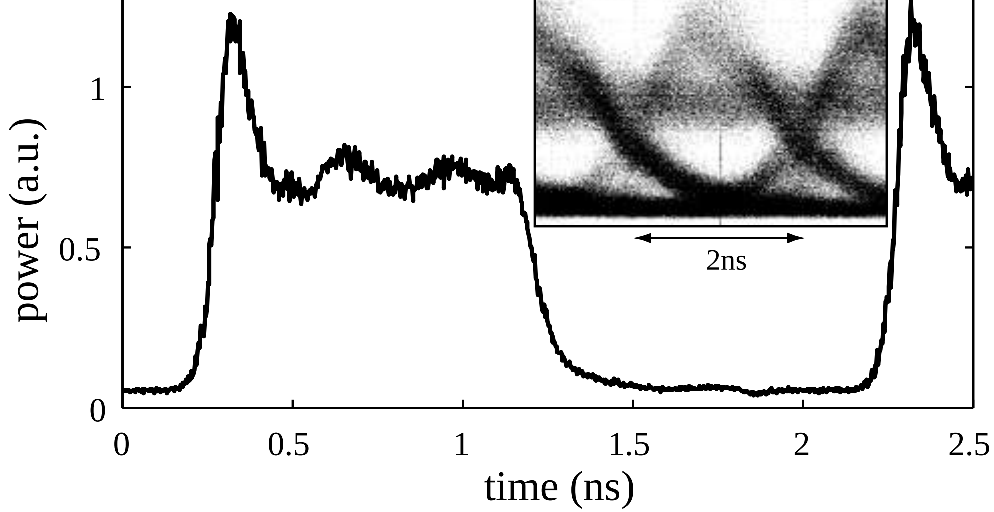
Targets in our new project (WADIMOS)

- Demonstrate improved device performance
  - Lower threshold power
  - Higher output power
  - More stable operation
- Demonstrate fabrication in CMOS pilot line
  - On 200mm wafers
  - Using CMOS tools
  - Using single epitaxial structure for source and detector
- Look at novel applications
  - High speed wavelength convertor
  - Operation as all-optical flip-flop

Ultra-low-power Wavelength conversion

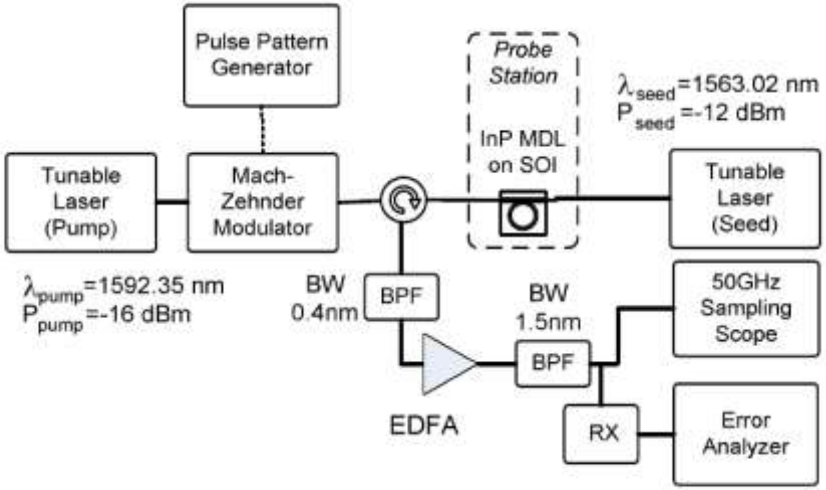






- No control power needed.
- Wavelength conversion with only 6.4uW control power.
- 5Gbps dynamic results.

Ultra low power wavelength conversion



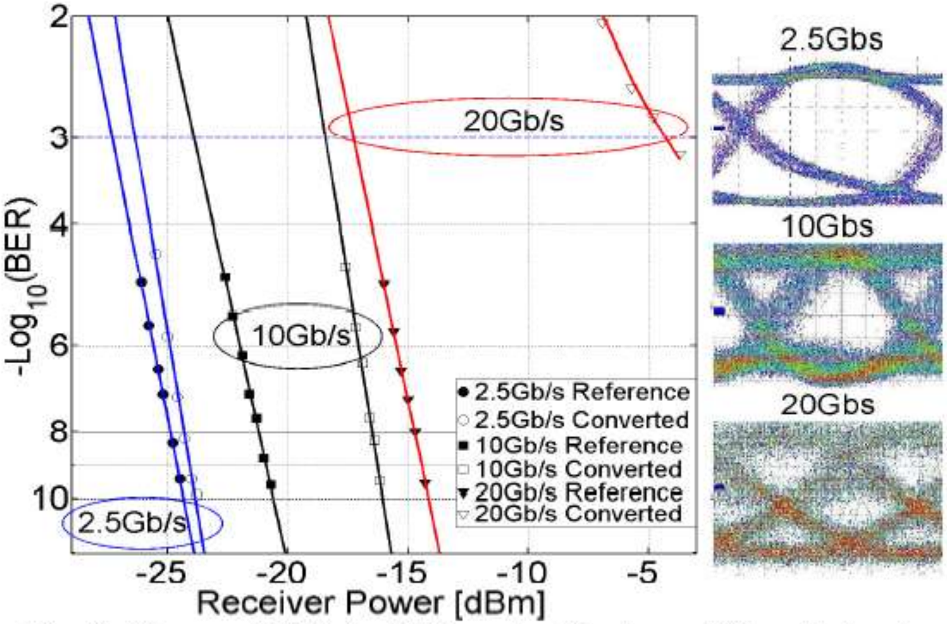


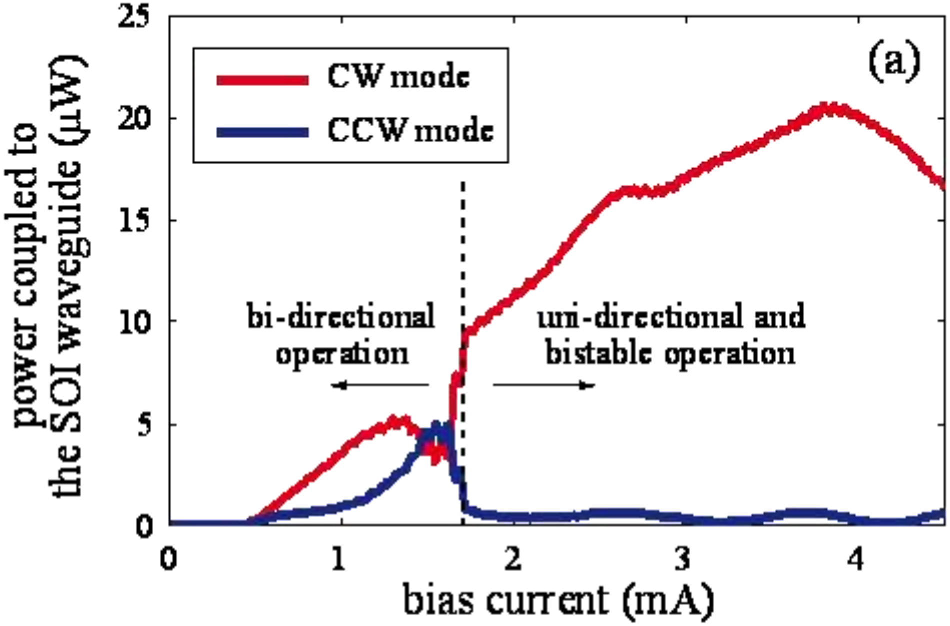
Fig. 5. Measured BER for MDL output for three different bit rates (eye patterns are given on the right)

	InP-SOA [4]/[5$^+$]	SOI [2]	SOI [3]	MDL
Top speed [Gb/s]	40/320$^+$	2.5*†	1*	10***
Power [mW]	1000/1000$^+$	200**	200**	10
Area [μm^2]	4000/2000$^+$	300	80	40
FOM	~$1\cdot10^{-5}/1.6\cdot10^{-4}$	~$5\cdot10^{-5}$	~$5\cdot10^{-5}$	$2.5\cdot10^{-2}$

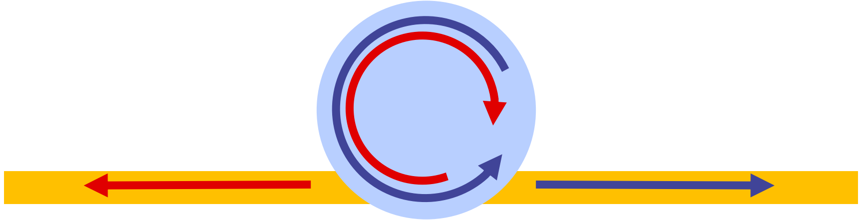
(O. Raz e.a. – submitted to OFC)

Microdisk as all-optical flip-flop

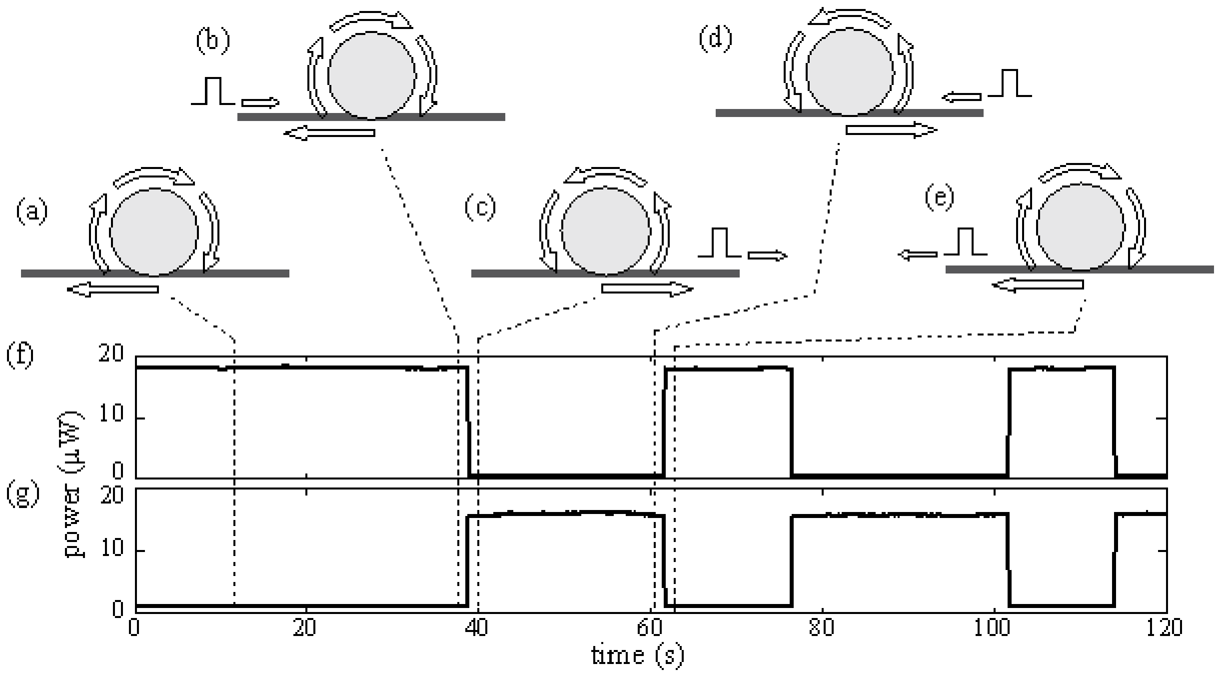
Microdisk as optical flip-flop

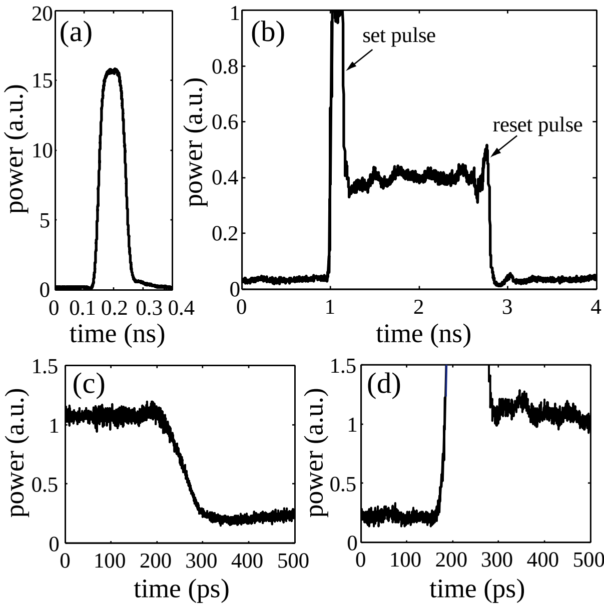


Bistable operation possible (CCW versus CW mode)



Microdisk as all-optical flip-flop





Stable operation demonstrated

- **100ps switch pulses with 1.8 fJ energy, bias current: 3.5 mA**

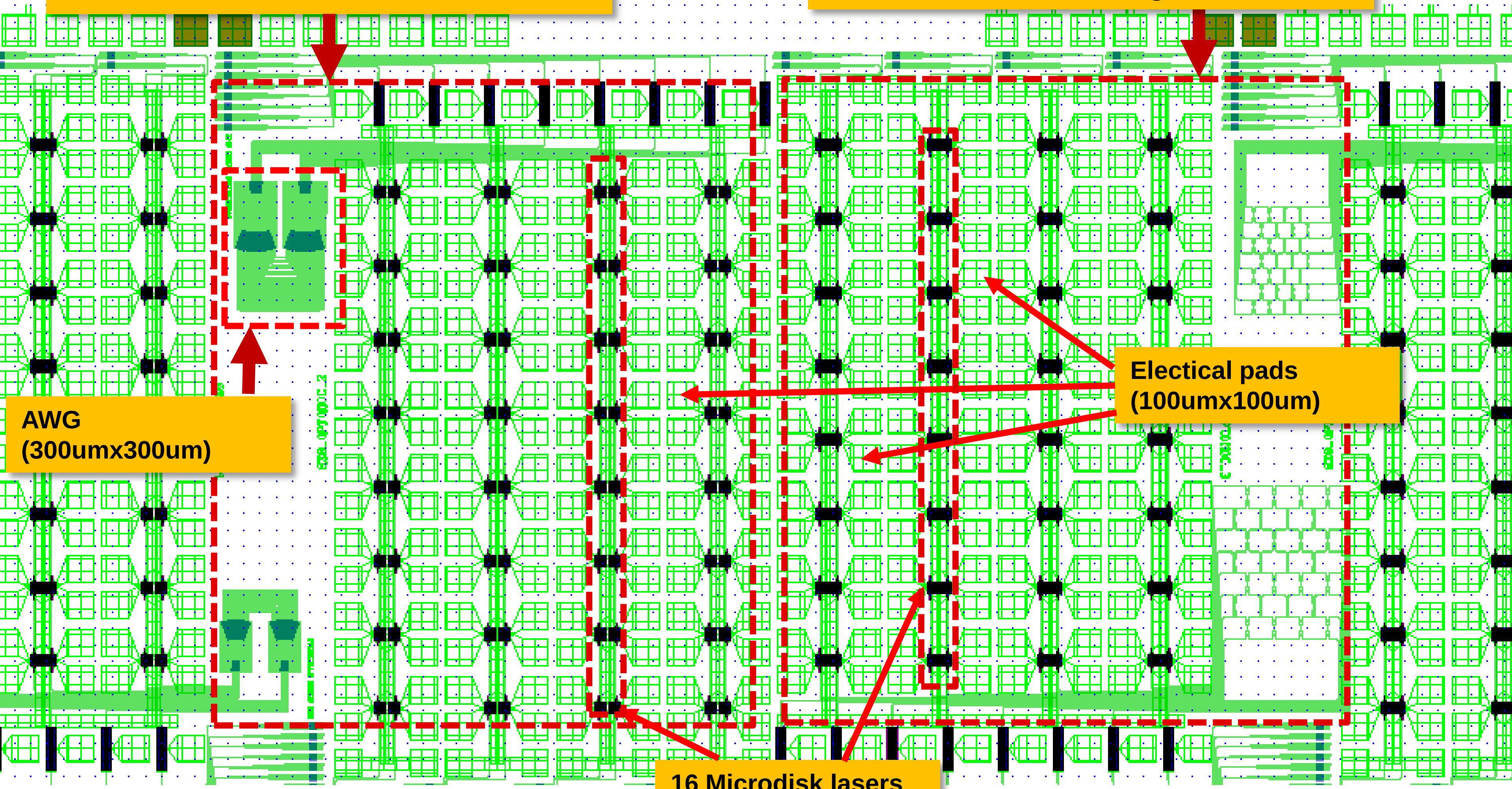
L. Liu, et al., ‘An ultra-small, low-power, all-optical flip-flop memory on a silicon chip’, Nature Photonics 2010

Microdisk lasers

Targets in our new project (WADIMOS)

- Demonstrate improved device performance
  - Lower threshold power
  - Higher output power
  - More stable operation
- Demonstrate fabrication in CMOS pilot line
  - On 200mm wafers
  - Using CMOS tools
  - Using single epitaxial structure for source and detector
- Look at novel applications
  - Operation as all-optical flip-flop
- What's next ?

WADIMOS demonstrator



8x8 network with AWG as router

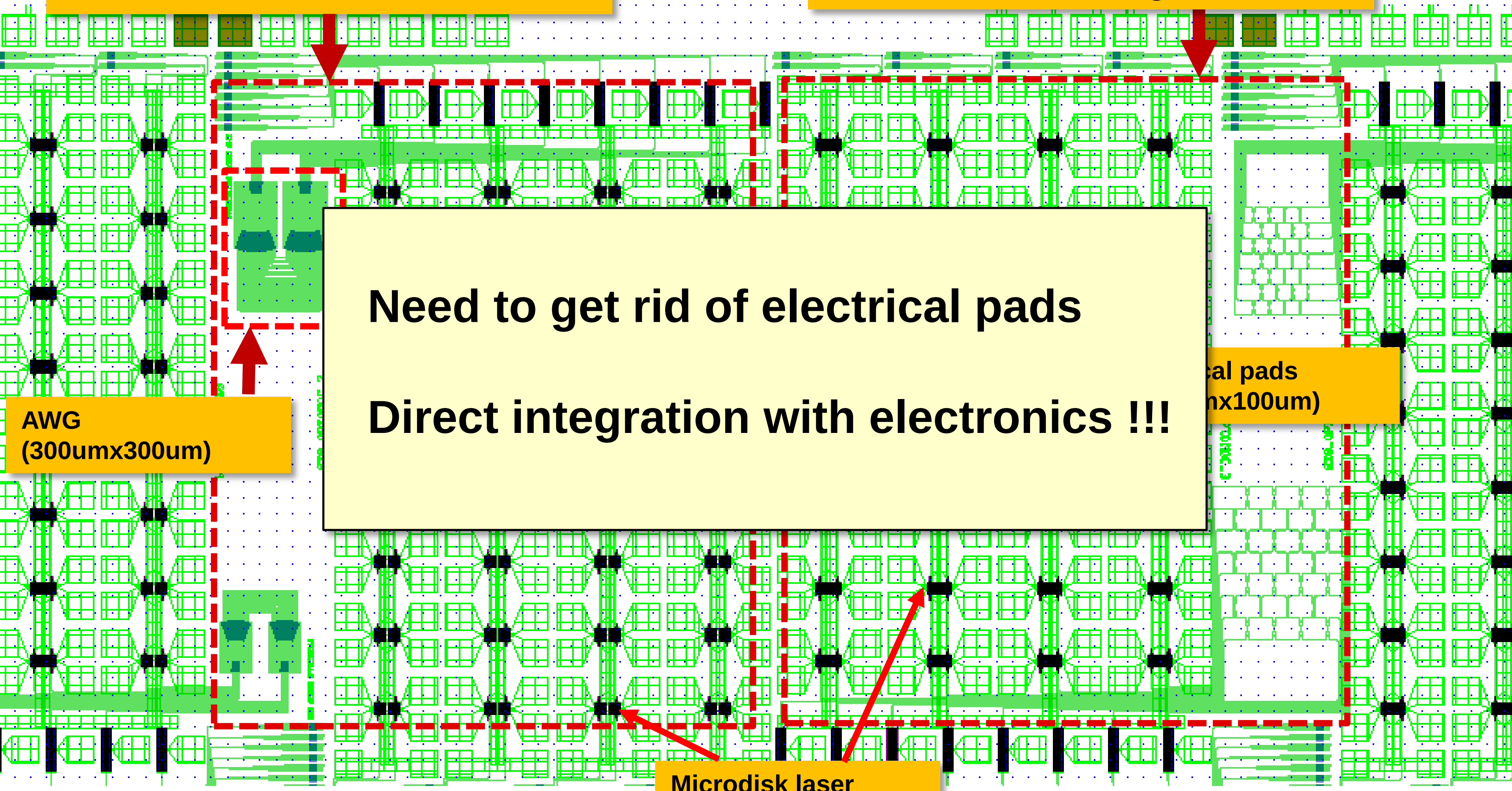
8x8 network with rings as router

AWG (300umx300um)

Electical pads (100umx100um)

16 Microdisk lasers (10umx10um)

WADIMOS demonstrator



8x8 network with AWG as router

8x8 network with rings as router

AWG
(300umx300um)

al pads
nx100um)

Microdisk laser
(10umx10um)

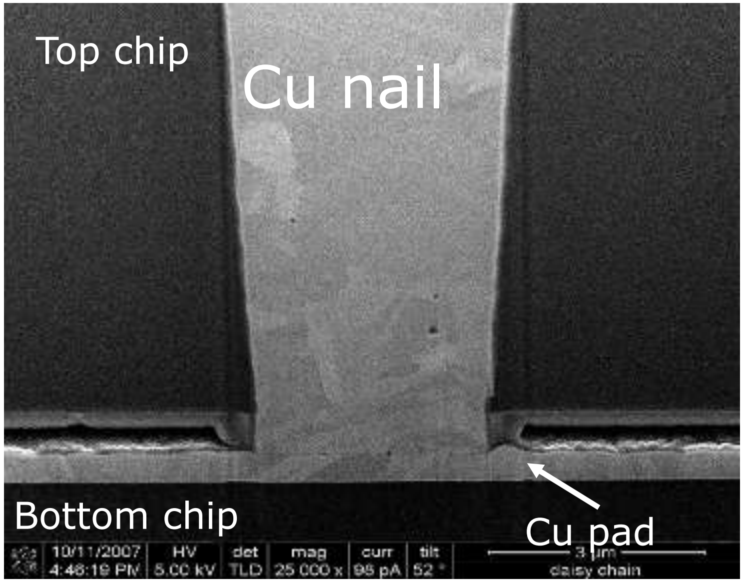
Need to get rid of electrical pads

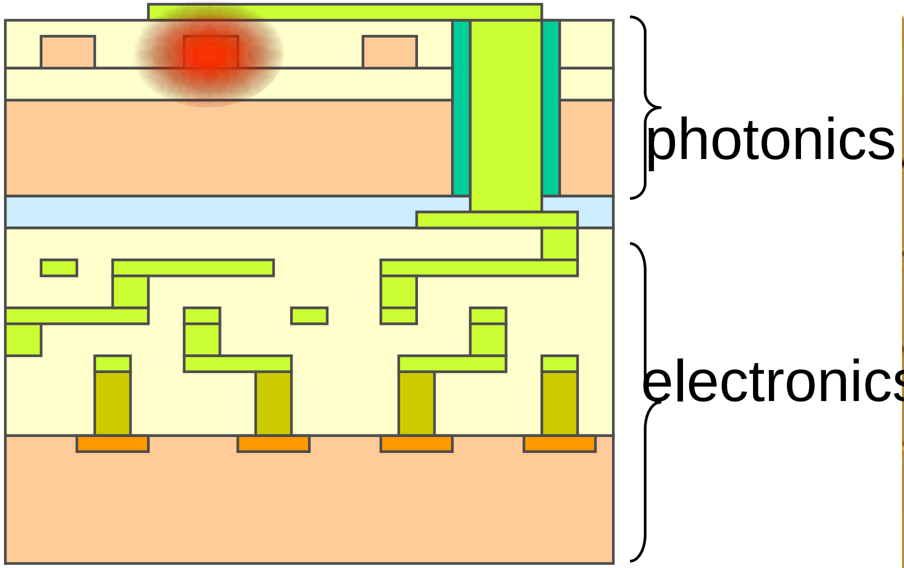
Direct integration with electronics !!!

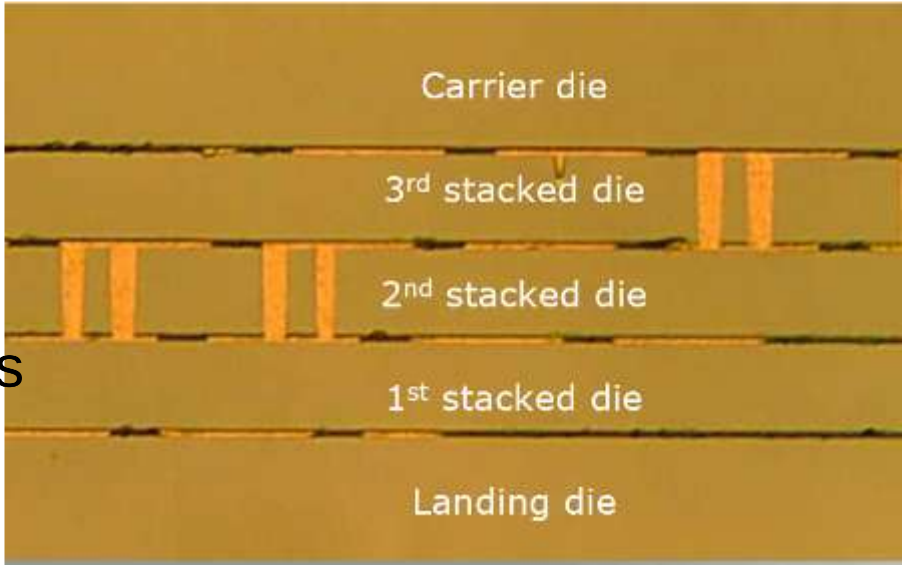
IMEC's Cu-nail technology

Technology in advanced stage

- demonstrated 4-layer chip stack (with interconnects only)
- via resistance ~ 30mOhm
- CMOS chip pair stack demonstrated





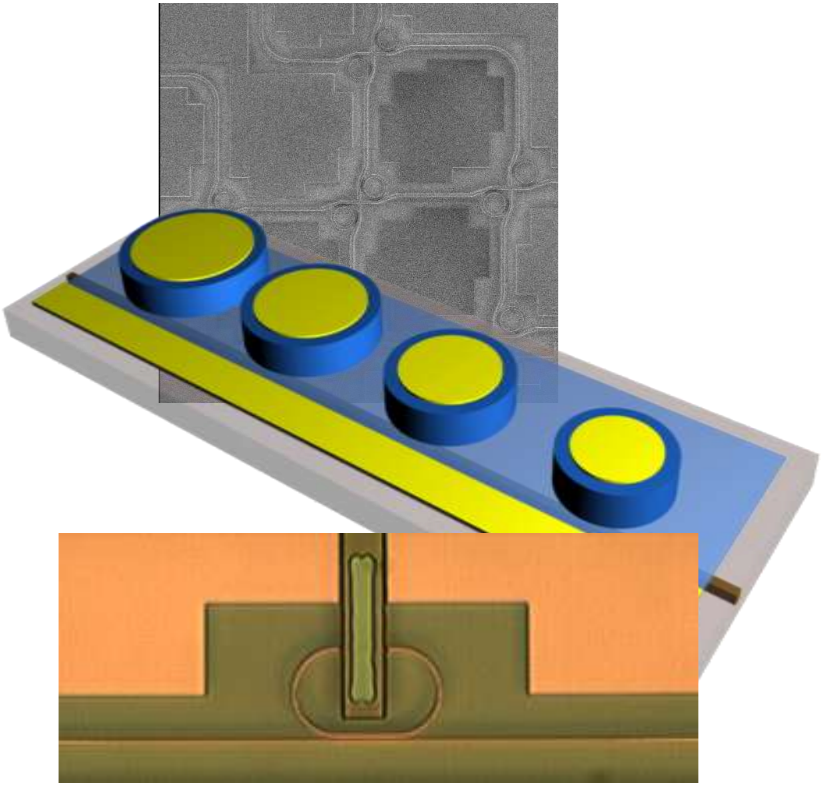


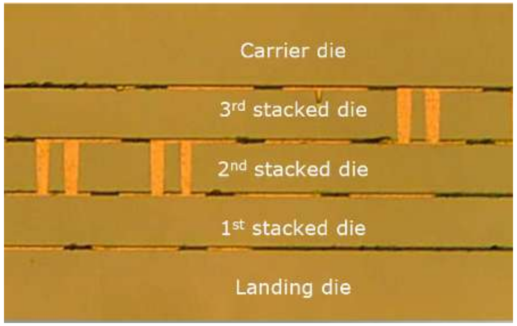
Outline

Outline

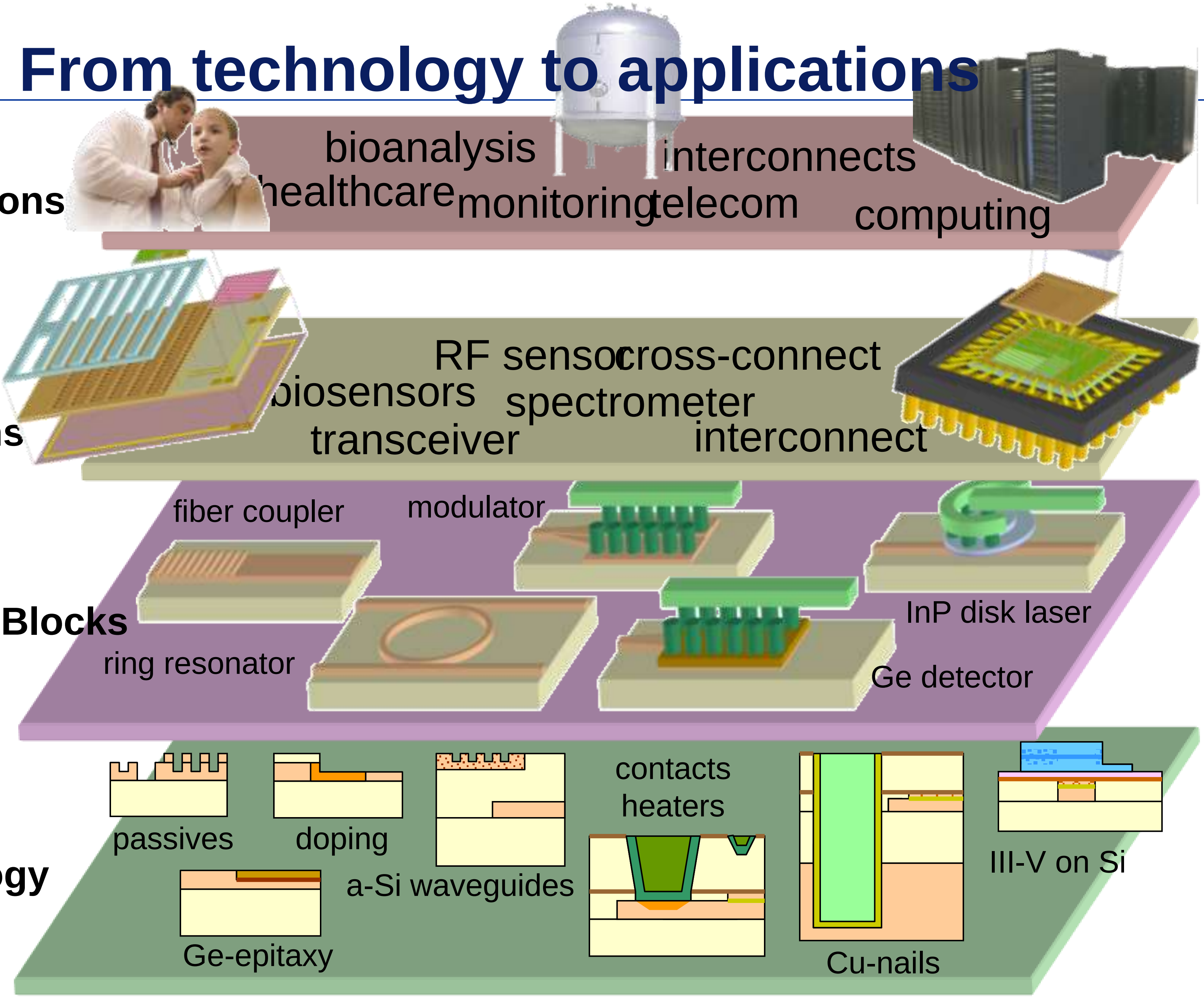
- Passive routing circuitry
- Multi-wavelength lasers
- Wavelength selective detectors
- Integration with electronics

- Some other applications …
- How to get access to technology





From technology to applications



Applications

bioanalysis

healthcare

monitoring

interconnects

telecom

computing

Functions

RF sensor

cross-connect

biosensors

spectrometer

transceiver

interconnect

Building Blocks

fiber coupler

modulator

InP disk laser

ring resonator

Ge detector

Technology

passives

doping

a-Si waveguides

contacts

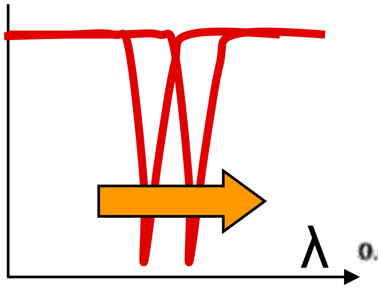
heaters

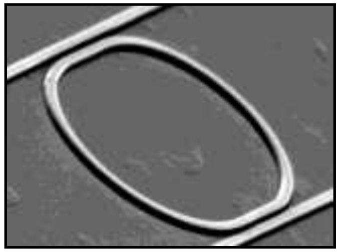
Ge-epitaxy

Cu-nails

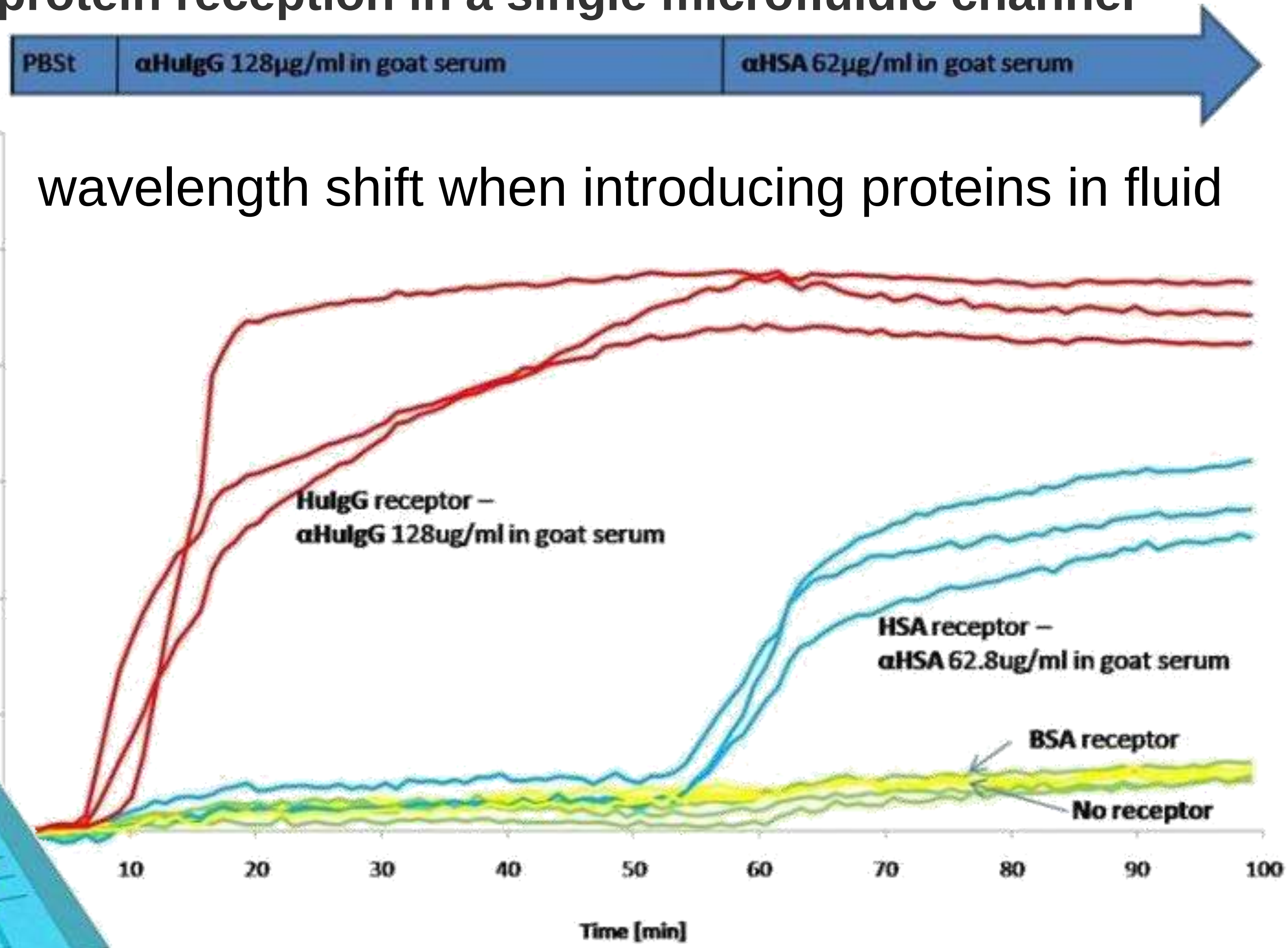
III-V on Si

Multiplexed protein detection

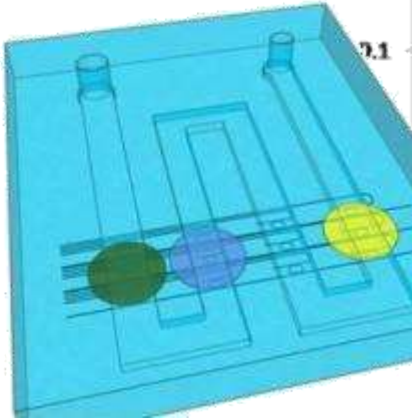




Different ring resonators functionalized for different protein reception in a single microfluidic channel

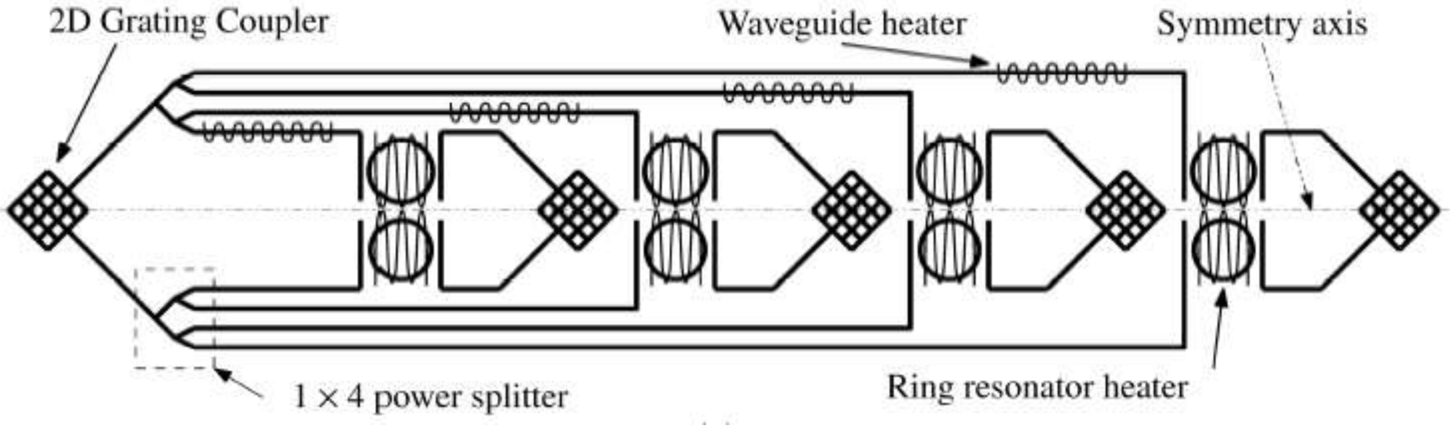


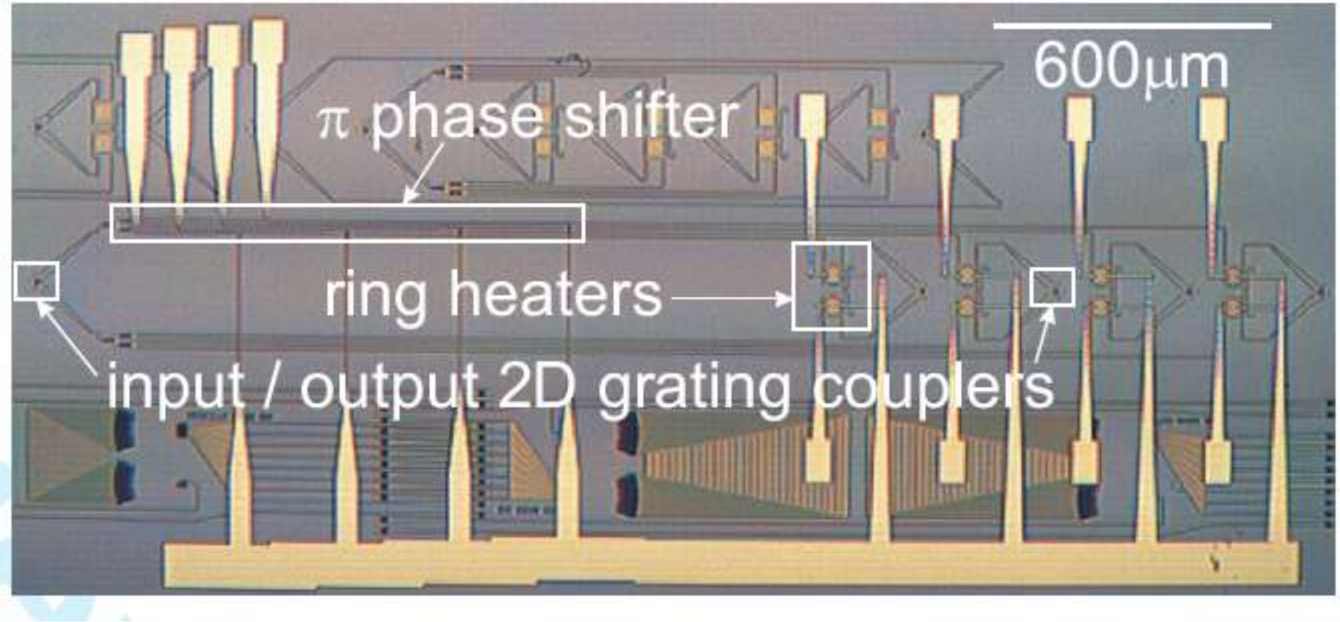
wavelength shift when introducing proteins in fluid



K. De Vos, LEOS AM 2009

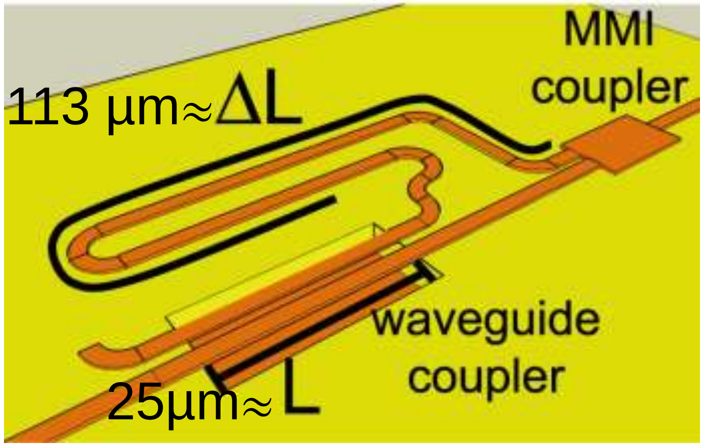
Optical router for WDM-PON

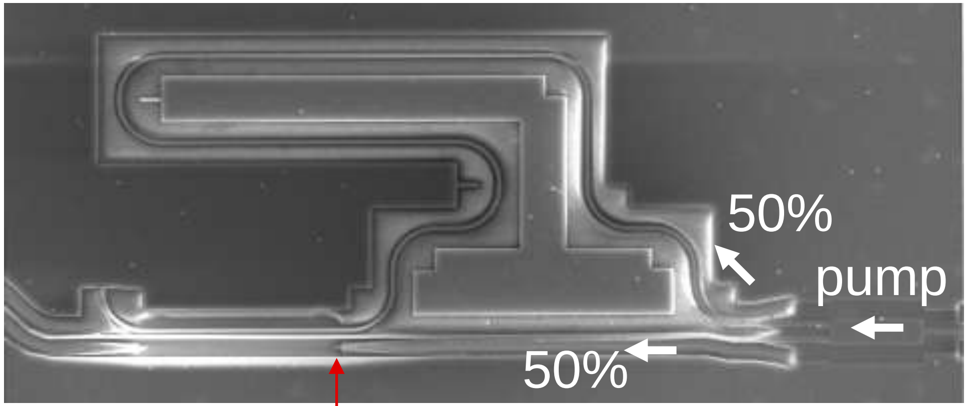




See Halir e.a. , OFC 2010, paper OWJ1

Optical force sensing

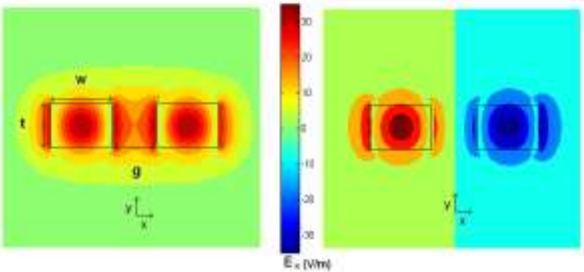




sweeping pump λ → fields arrive with different phase at waveguide coupler entrance

in phase fields favor symmetric (attractive)

counter phase fields favor anti-symmetric (repulsive) mode

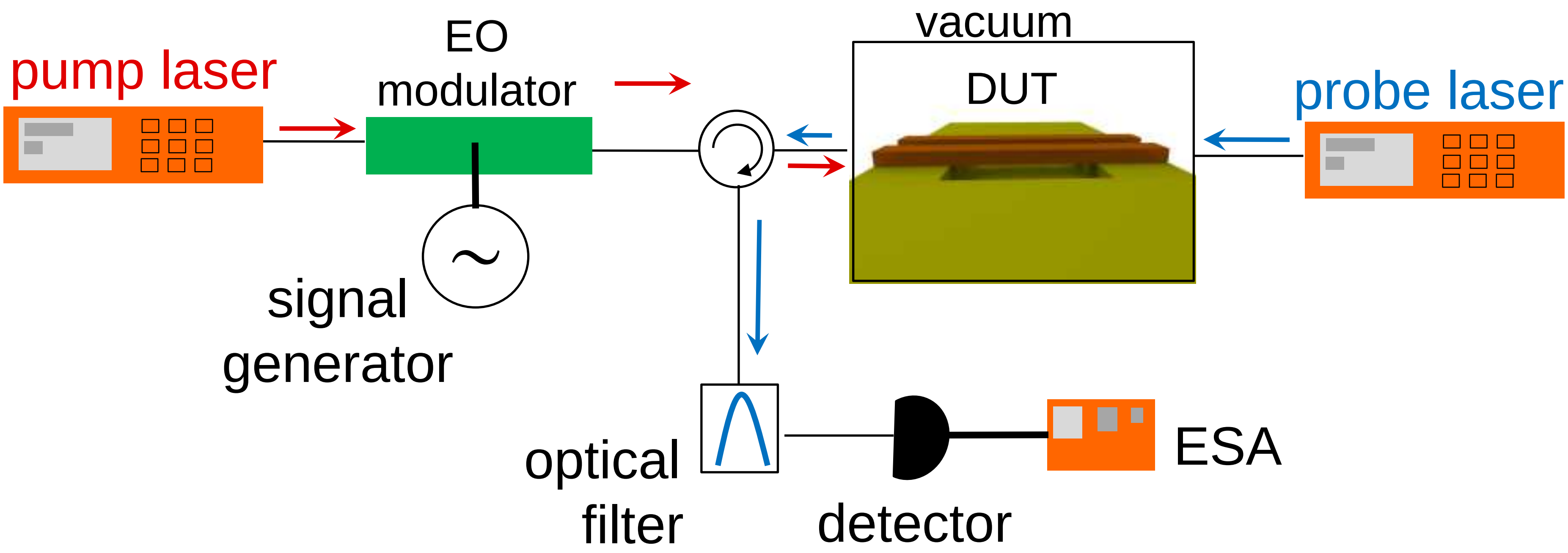


symmetric

anti-symmetric

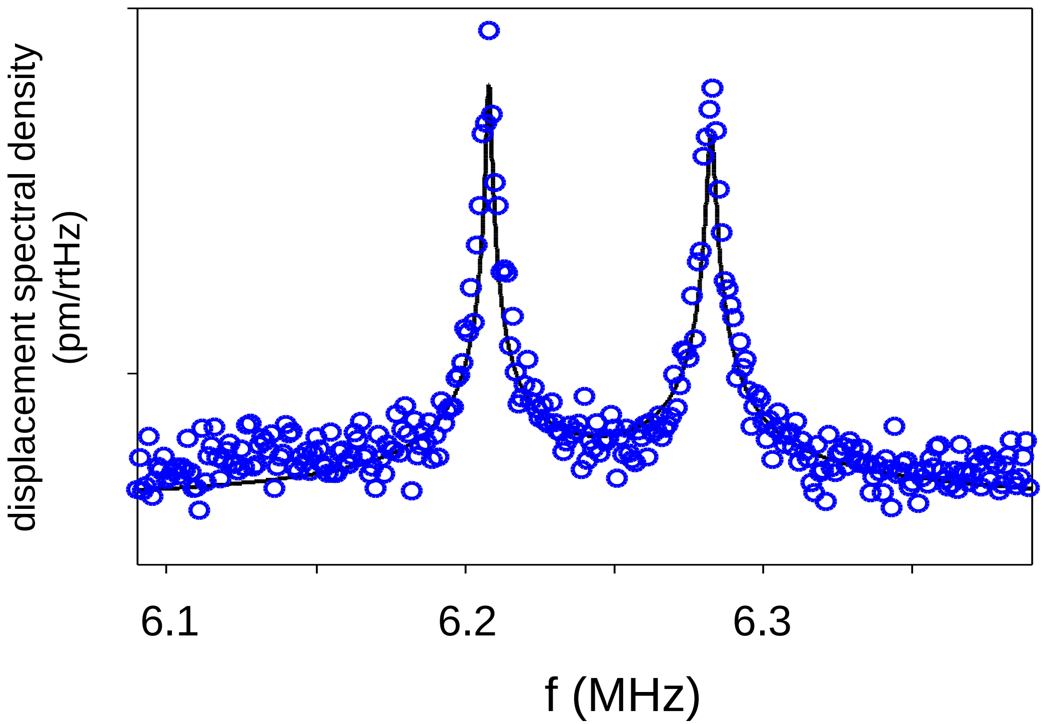
sweeping wavelength enables tuning: attractive ↔ repulsive

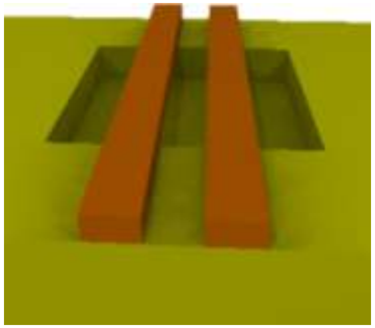
Experimental set-up



- pump laser is power modulated to achieve resonant excitation
- Device-Under-Test is placed in vacuum to decrease air damping (Q_{mech}↑)

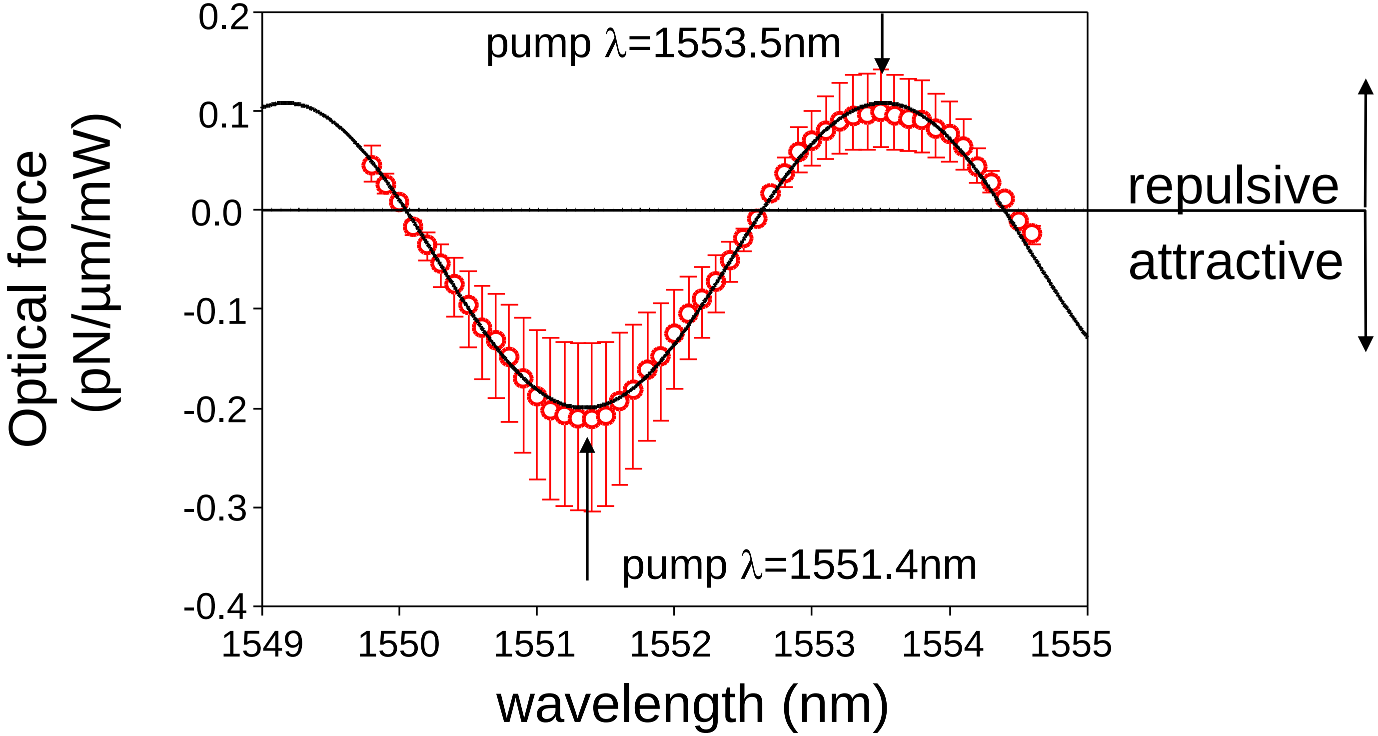
Motion transduction calibration





- 2 peaks (2 freestanding waveguides = 2 harmonic oscillators)
- ‘brownian’ force in bandwidth B: $$F_{brown} = \sqrt{\frac{4k_b T m_{eff} \omega_{res} B}{Q_{mech}}}$$
- can be used for calibration of other forces (electrical, optical)

Tunable force



Excellent agreement theory vs. experiment

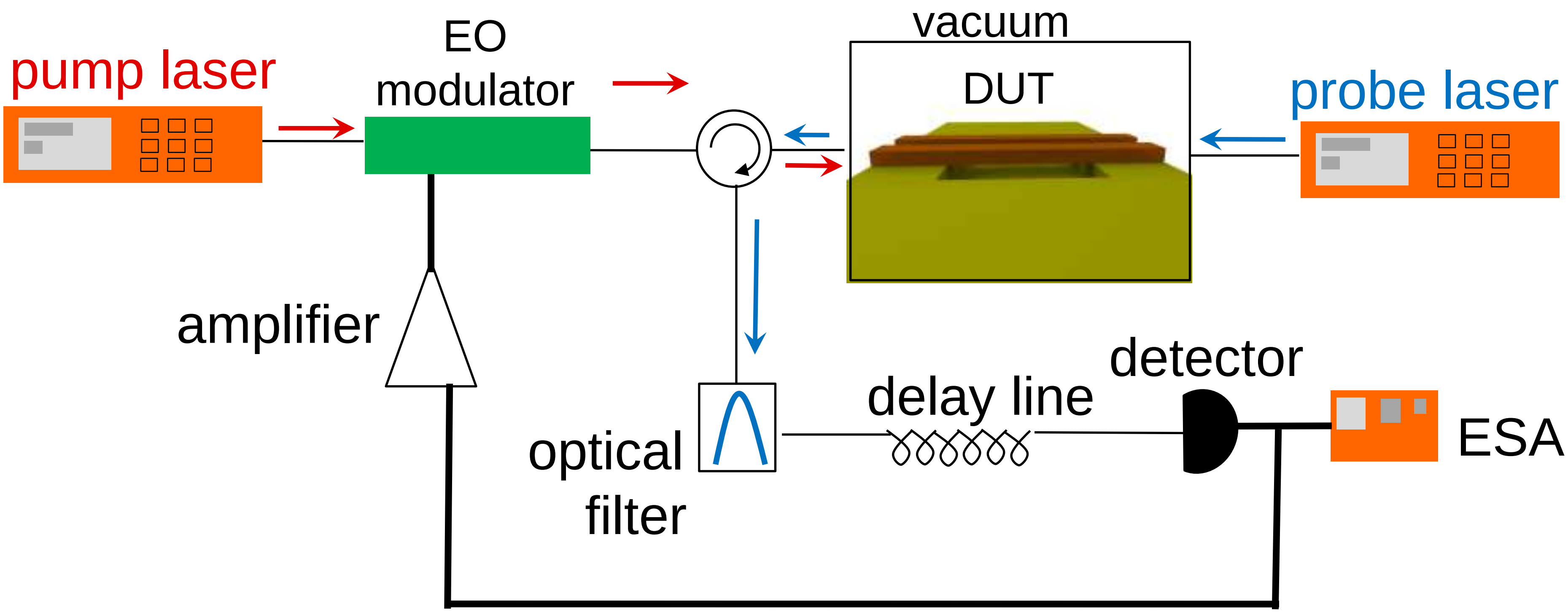
- $F_{\text{symm,att}}$ □ -0.2pN/µm/mW
- $F_{\text{antisymm,rep}}$ □ 0.1pN/µm/mW

Experimental demonstration: attractive vs. repulsive force

J. Roels et al., Tunable optical forces between nanophotonic waveguides, Nat. Nanotechnology (2009)

M. Li et al., Tunable bipolar optical interactions between guided lightwaves, Nat. Photonics (2009)

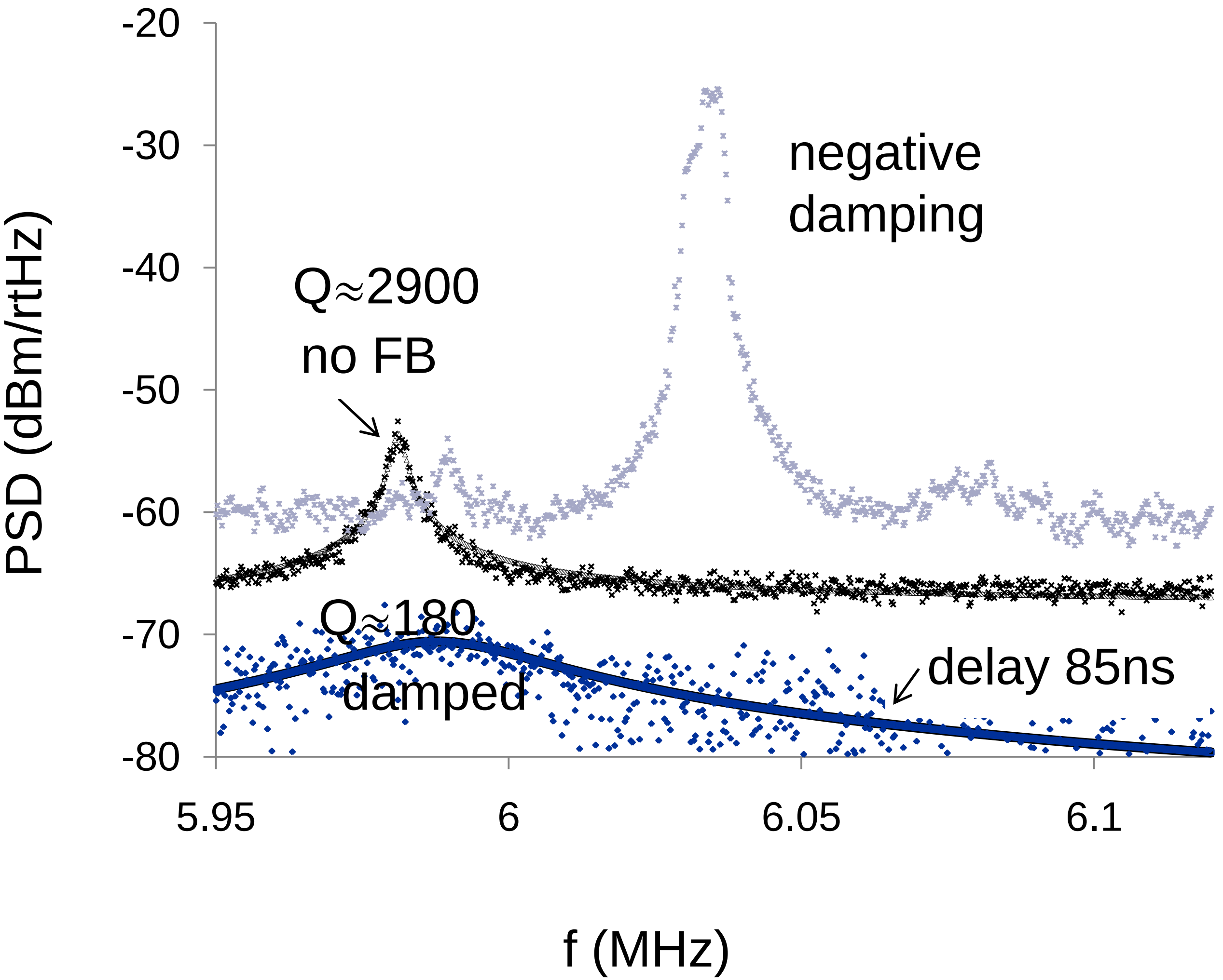
Feed-back cooling/heating



- modulation signal of the pump laser is provided by the brownian motion of the waveguide string
- tunable delay line: phase shift between feedback force F(t) and waveguide movement x(t)

Feed-back cooling/heating

$$k\,x(t) + \Gamma\,\dot{x}(t) + m\,\ddot{x}(t) = F_{brown} + F_{FB,OPT}(t)$$



Feedback force:

*Positive/negative damping dependent on delay line length

*delay pos. vs. neg. damping ±85ns≈π

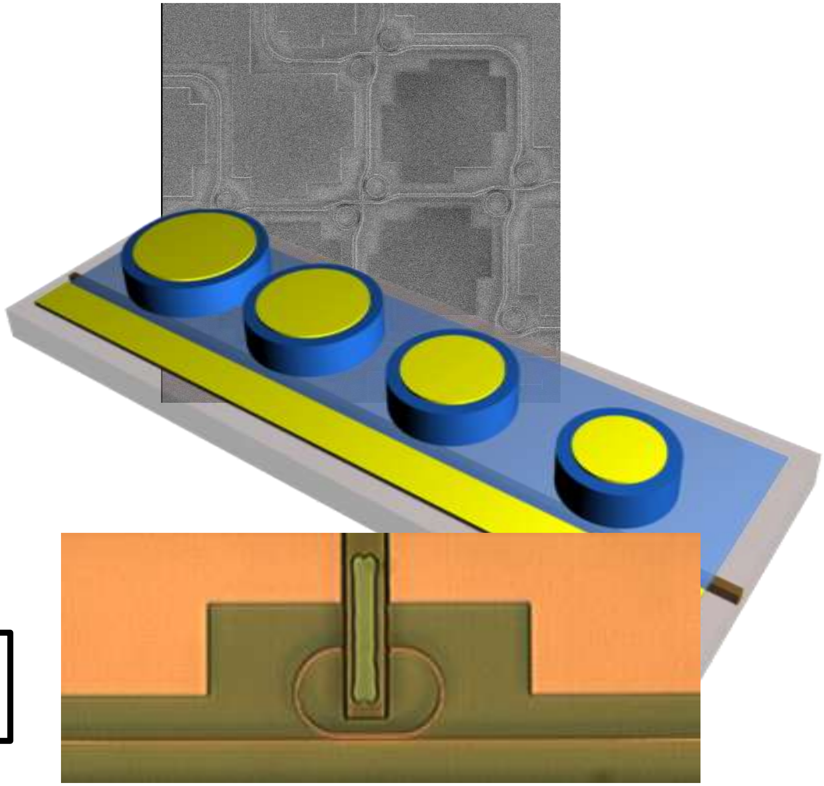
*RF-filter with tunable width

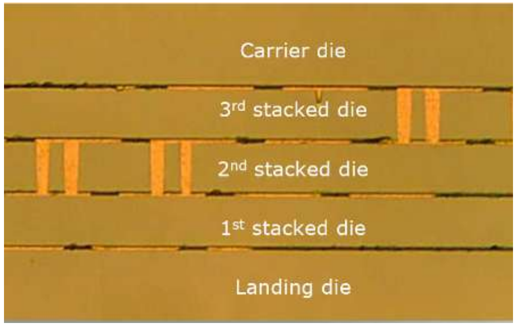
Outline

Outline

- Passive routing circuitry
- Multi-wavelength lasers
- Wavelength selective detectors
- Integration with electronics

- Some other applications …
- **How to get access to technology**





ePIXfab

Silicon photonics in CMOS fab

- Cheap for volume production
- Expensive and difficult access for research and prototyping

Solution ? ePIXfab

- Multi-project wafer shuttles allow cost sharing
- Joint initiative of IMEC and LETI
- Supported by EU-commission
- Open for research and prototyping

ePIXfab

Silicon photonic IC prototyping service

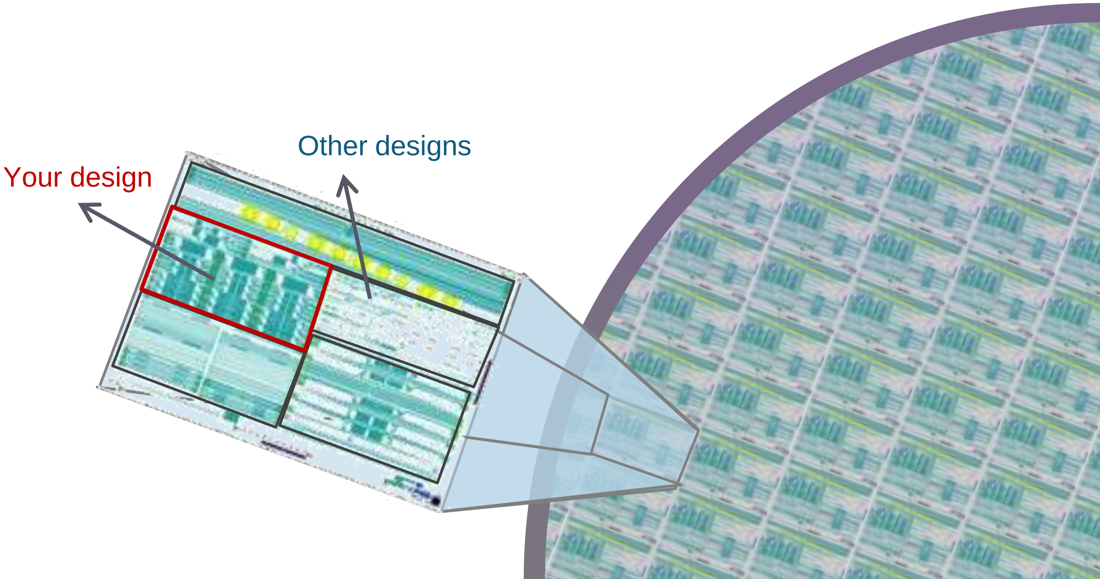
- **Multi project wafer shuttles – cost sharing**
- **Based on unique silicon process capabilities**
- **World-wide client base**

Drive market adoption

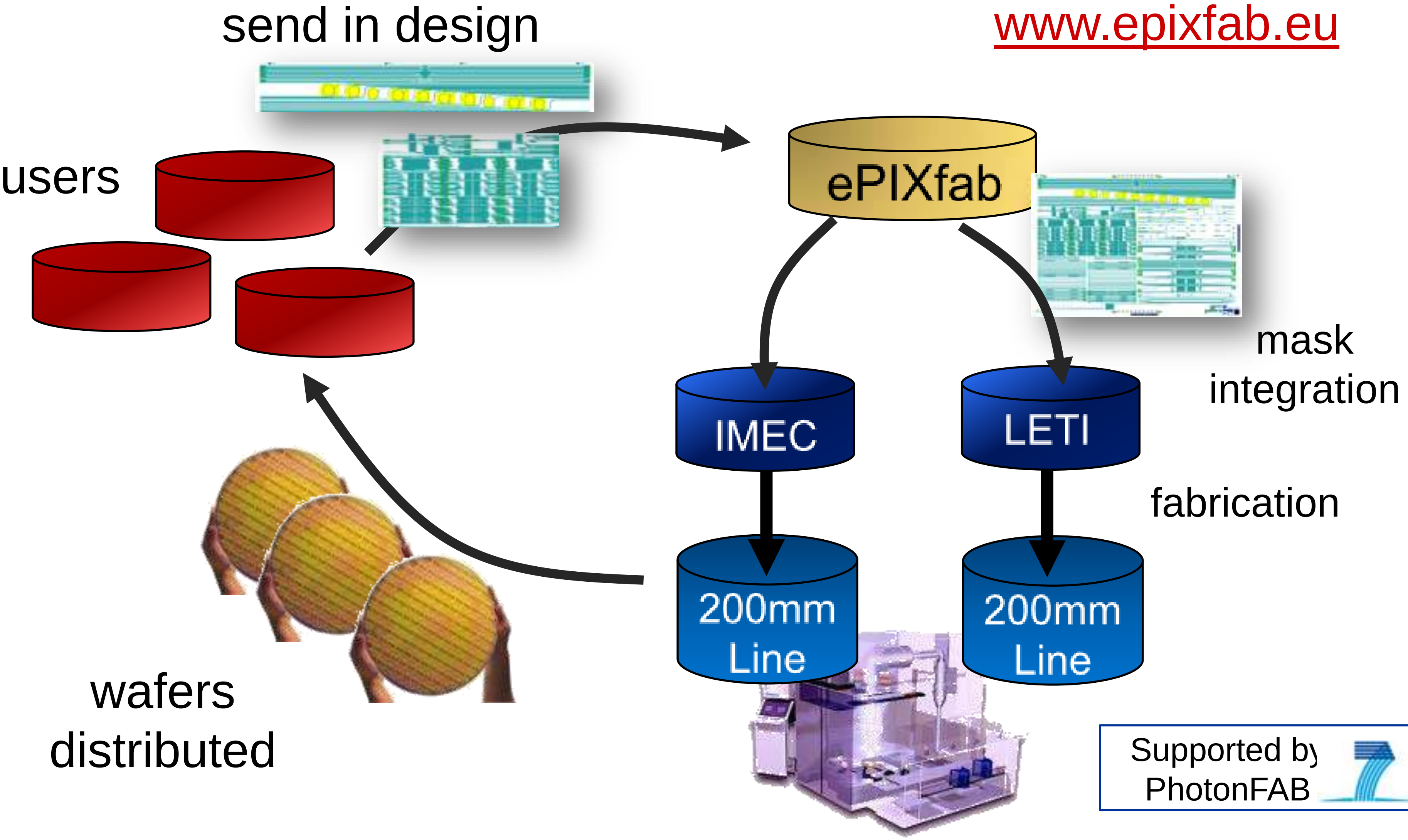
- **Enable cost-effective circuit-level R&D**
- **Involve the stakeholders**

Since Sept 2006:

- **> 30 institutes**
- **> 100 designs**



ePIXfab: serving the research community



www.epixfab.eu

send in design

users

ePIXfab

IMEC

LETI

mask
integration

fabrication

200mm
Line

200mm
Line

wafers
distributed

Supported b
PhotonFAB

ePIXfab: Practical information

Visit our web site:

www.epixfab.eu or www.siliconphotonics.eu

- **Information on calls**
- **Technical docs**

Coordinator:

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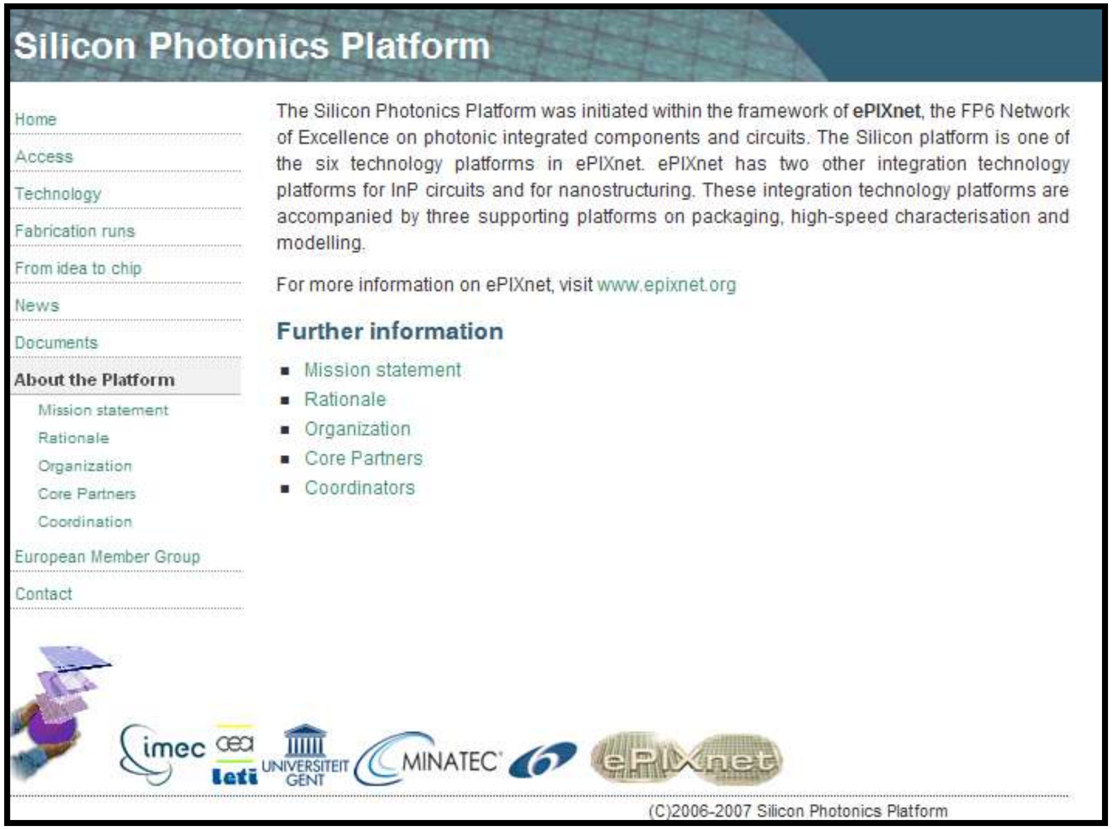

Silicon Photonics Platform

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The Silicon Photonics Platform was initiated within the framework of **ePIXnet**, the FP6 Network of Excellence on photonic integrated components and circuits. The Silicon platform is one of the six technology platforms in ePIXnet. ePIXnet has two other integration technology platforms for InP circuits and for nanostructuring. These integration technology platforms are accompanied by three supporting platforms on packaging, high-speed characterisation and modelling.

For more information on ePIXnet, visit www.epixnet.org

Further information

- Mission statement
- Rationale
- Organization
- Core Partners
- Coordinators

(C)2006-2007 Silicon Photonics Platform

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    - G. Duan (35labs)

Vacancies for PhD-students sep. 2011: check www.photonics.intec.ugent.be from Jan. 2011 on