leti innovation for industry

Hybrid Si/III-V Lasers with Adiabatic Coupling

B. Ben Bakir
CEA, LETI, Minatec Campus
Grenoble, France

MINATEC CAMPUS

A laser on silicon?

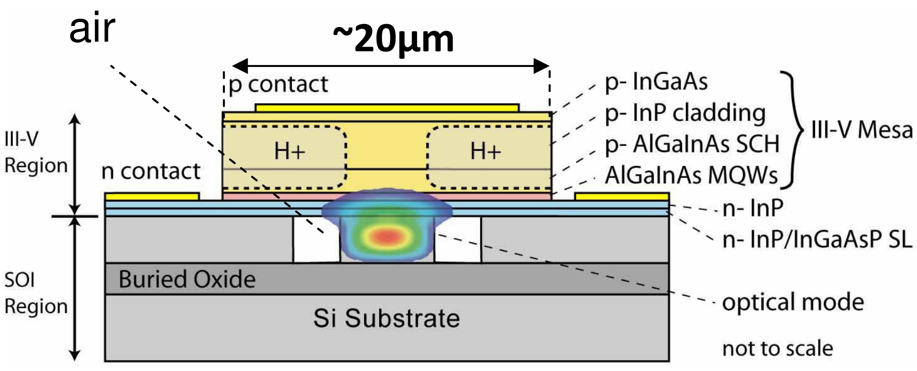
- Silicon (Ge, Si-nc+Er…) is a poor light emitter→ No integrated & electrically driven laser sources achievable in the short-medium term

- III-V materials exhibit excellent laser properties:
  - Direct growth of III-V materials has been studied for decades, but no convincing results up to now
  - Flip-chip bonding of lasers is a mature but rather expensive technology. Less flexibility in the laser design

➡ **Heterogeneous integration by direct bonding:** offers the best compromise between performances/ functionality/ manufacturability

Heterogeneous integration options

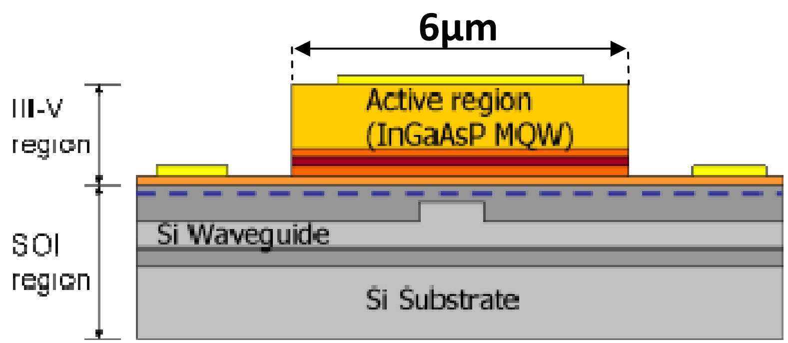
1. Direct bonding on Si



- Direct bonding of InP wafers on SOI without oxide layer
- Si waveguide / mode profile
  - Invariant along Z-direction
  - Mode mainly concentrated in Si-Wg (~70%)
- QWs confinement factor (~3%, 9 QWs)
- ☹ Integration with other active components (Si-modulators, Ge photodetectors)

UCSB/INTEL

2. Encapsulation/Planarization/Bonding



- Different Si waveguide heights, widths
  - ☺ Integration with other active components (Si-modulators, Ge photodetectors)
- Mode engineering along Z-direction
  - QWs confinement factor (~13%, 5 QWs)
  - Coupling efficiency → Si-wg: >95% (tapers)

LETI (molecular bonding)
IMEC (Polymer bonding)

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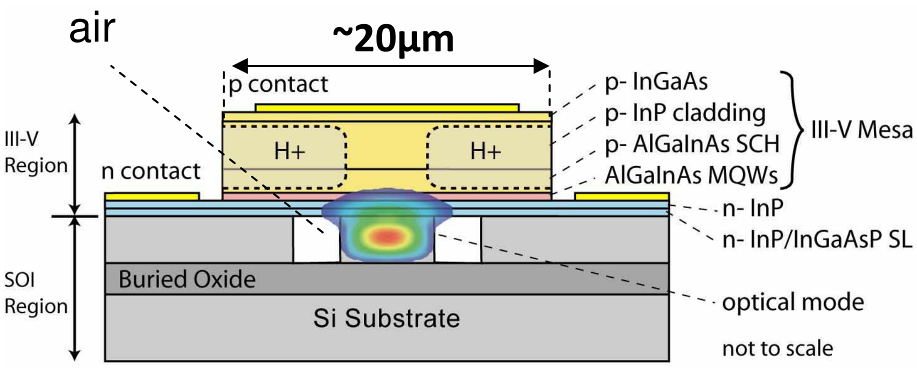

- Direct bonding of IIIV (InP) wafers on SOI without SiO2 spacing layer
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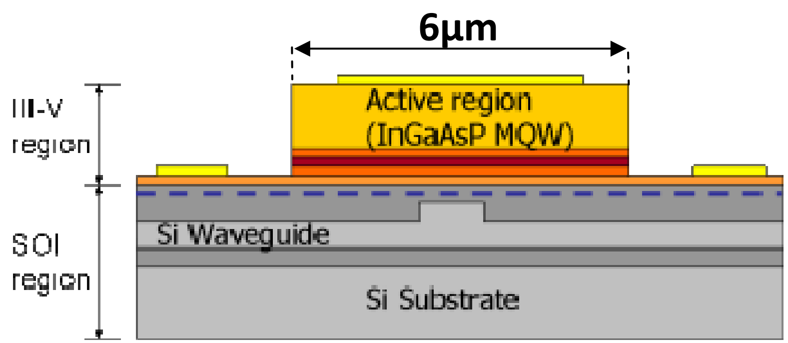

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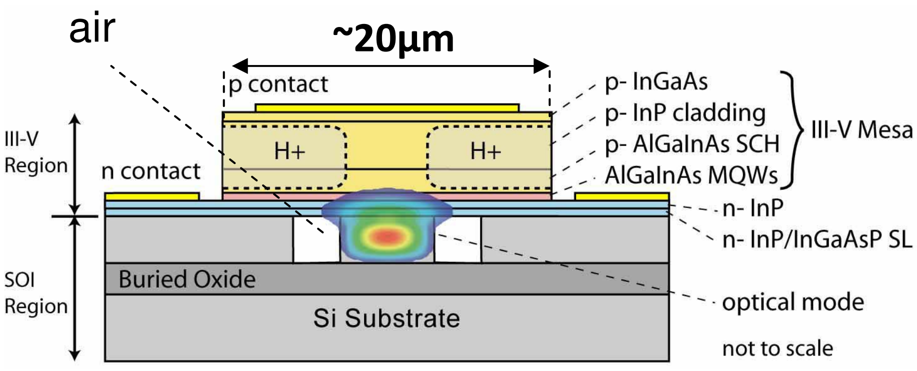

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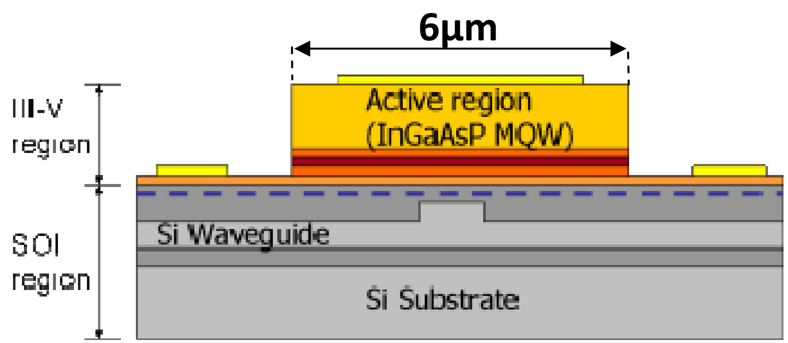

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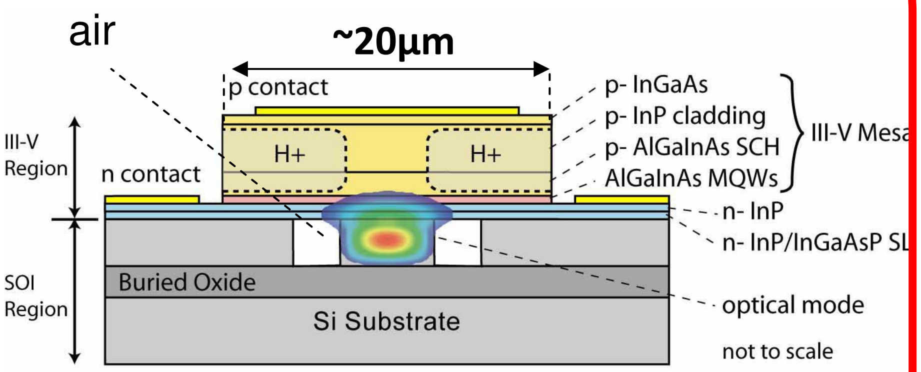

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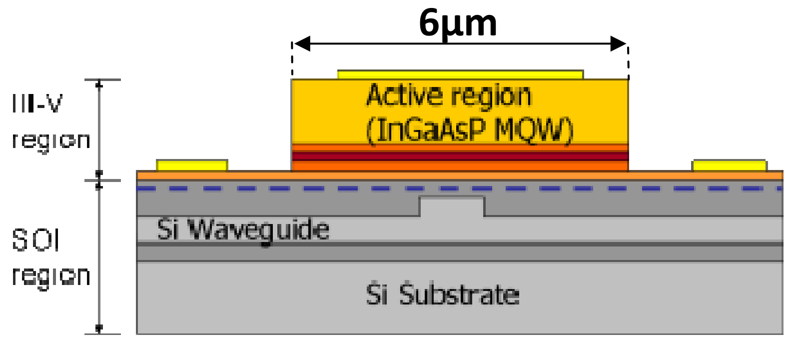

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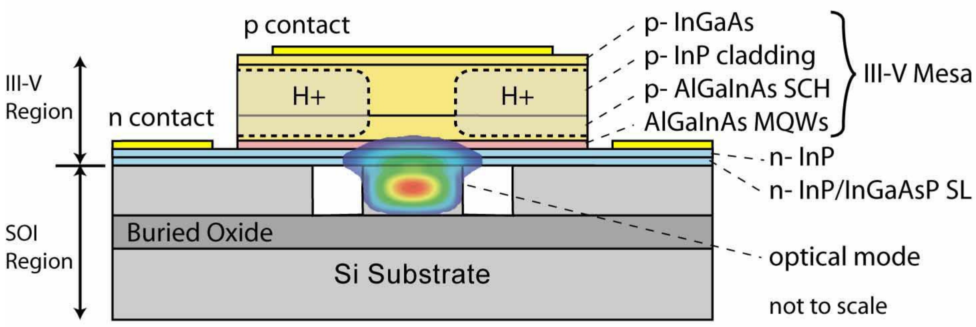
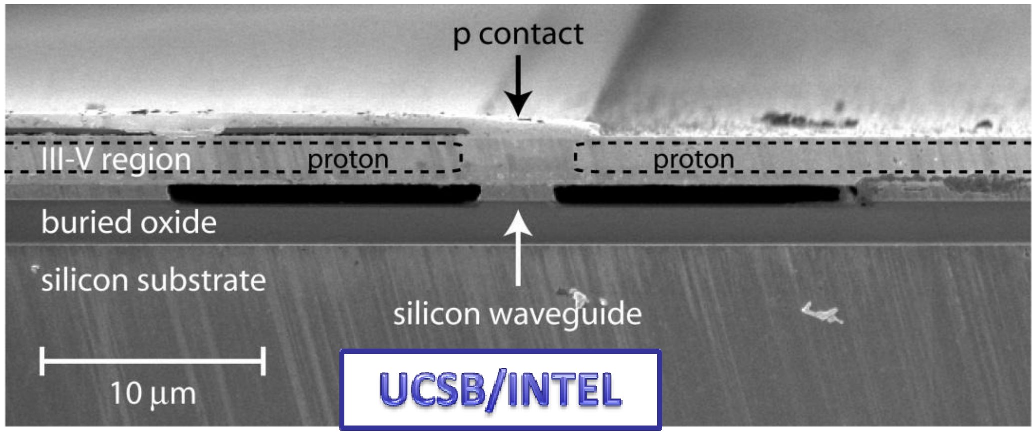
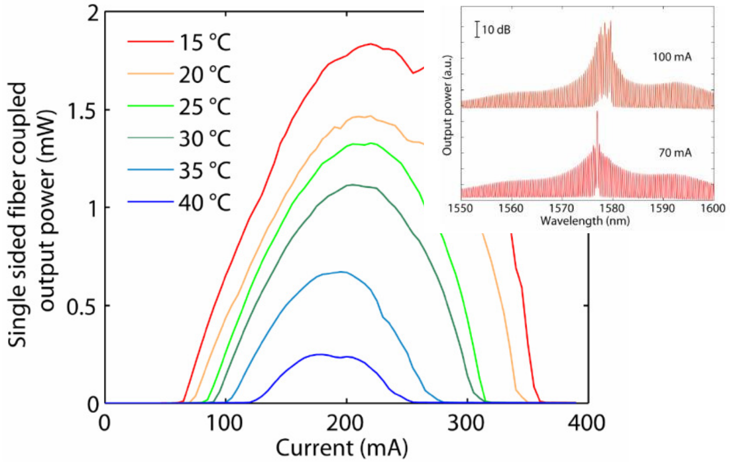
Fabry-Pérot lasers





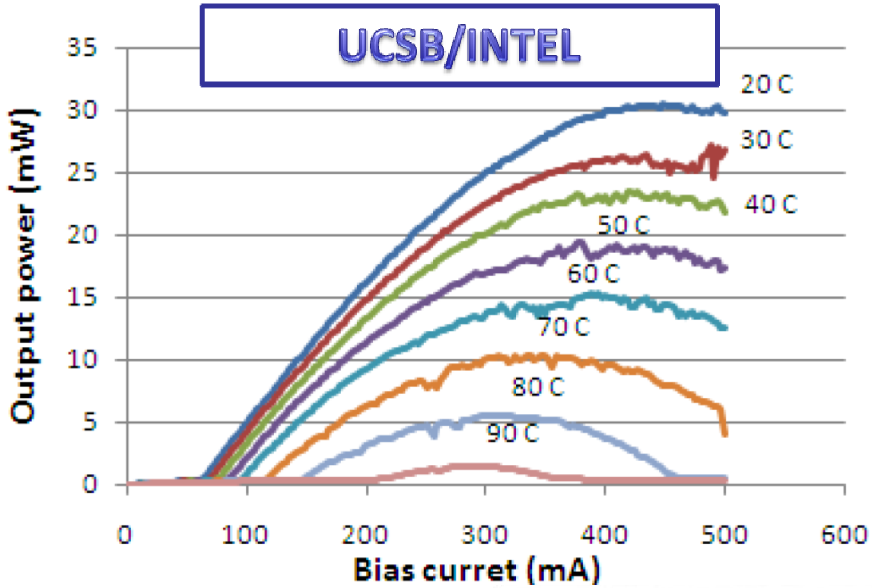
A. W. Fang *et al.* Opt. Express (2006).

- F-P cavity:
  - 860µm
  - ~30 % Si-to-air facet reflection
- Confinement factors:
  - Γ_{QWs}=3%
  - Γ_{Si}=75%



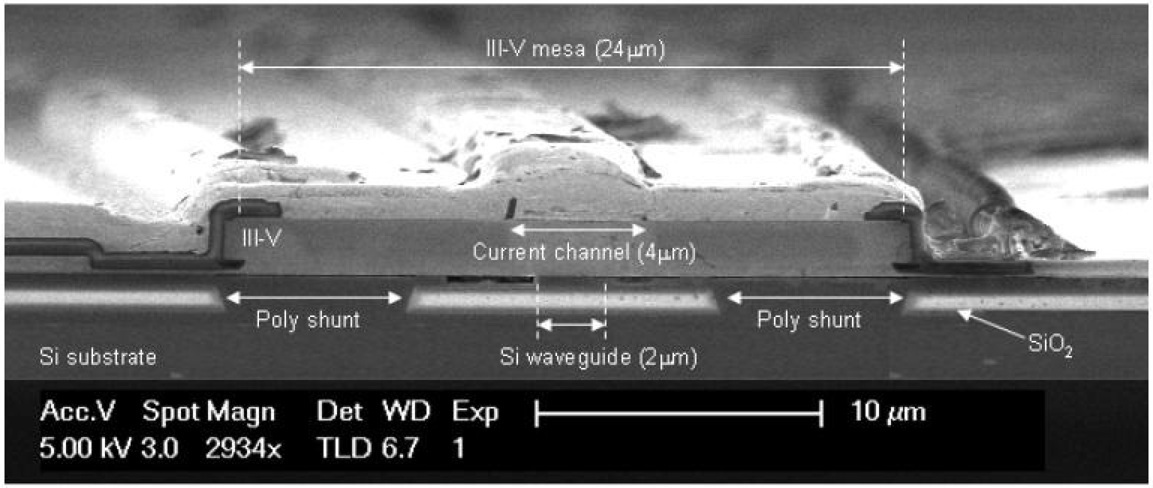
- I_{th} =65mA, P_{max} ~1.8mW @ 15°C (Single sided fiber coupled output power)
- Threshold voltage=2V
- Operating @ 40°C

Fabry-Pérot lasers (@ 1.3µm)

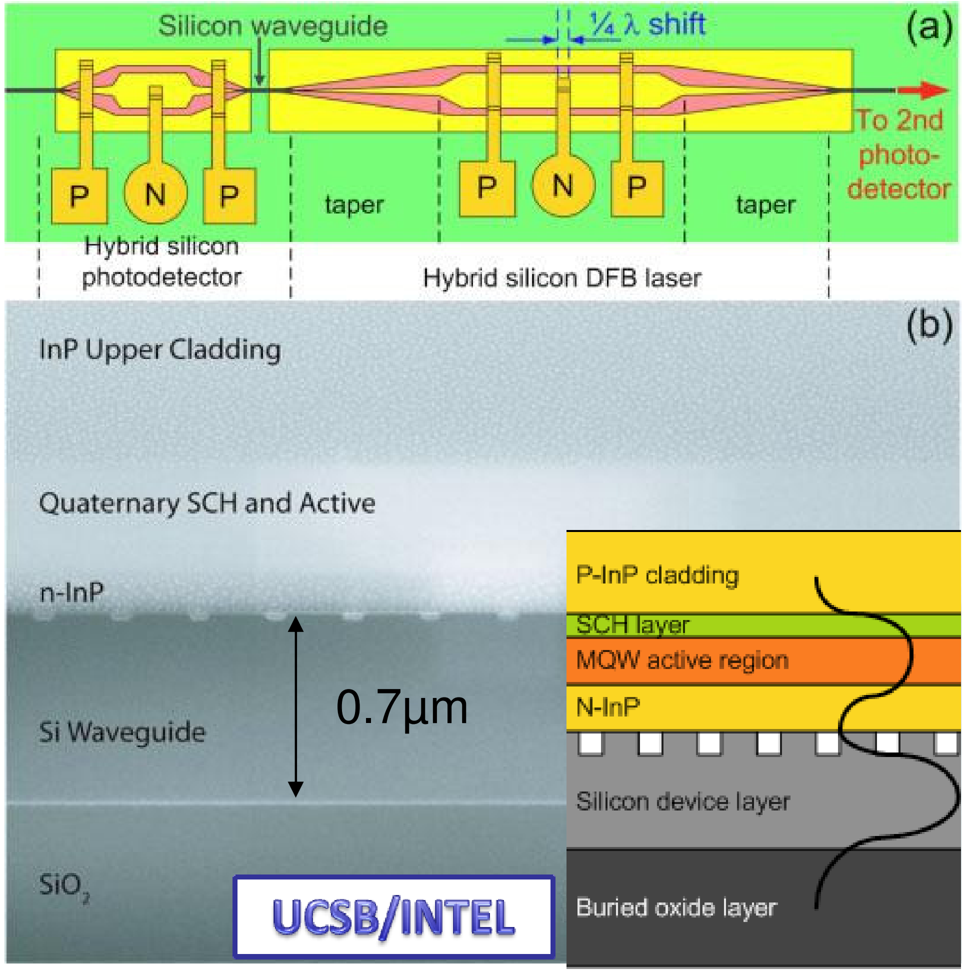


- 1.3µm CW @ 90°C
- Use poly-silicon thermal shunts to reduce the thermal impedance by 20%

M.N. Sysak *et al.* OFC'11

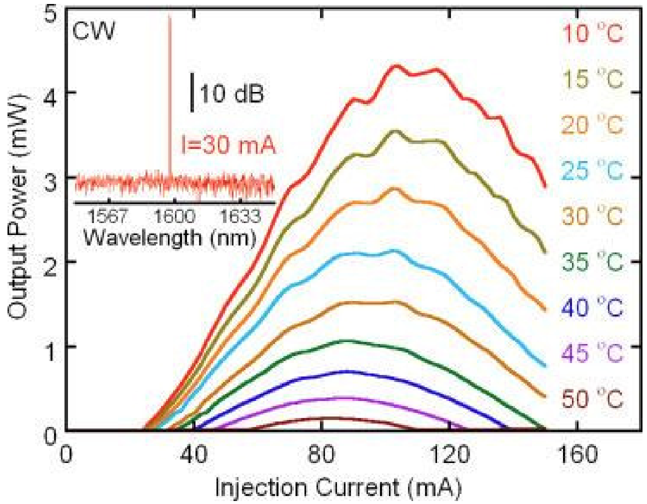


DFB lasers



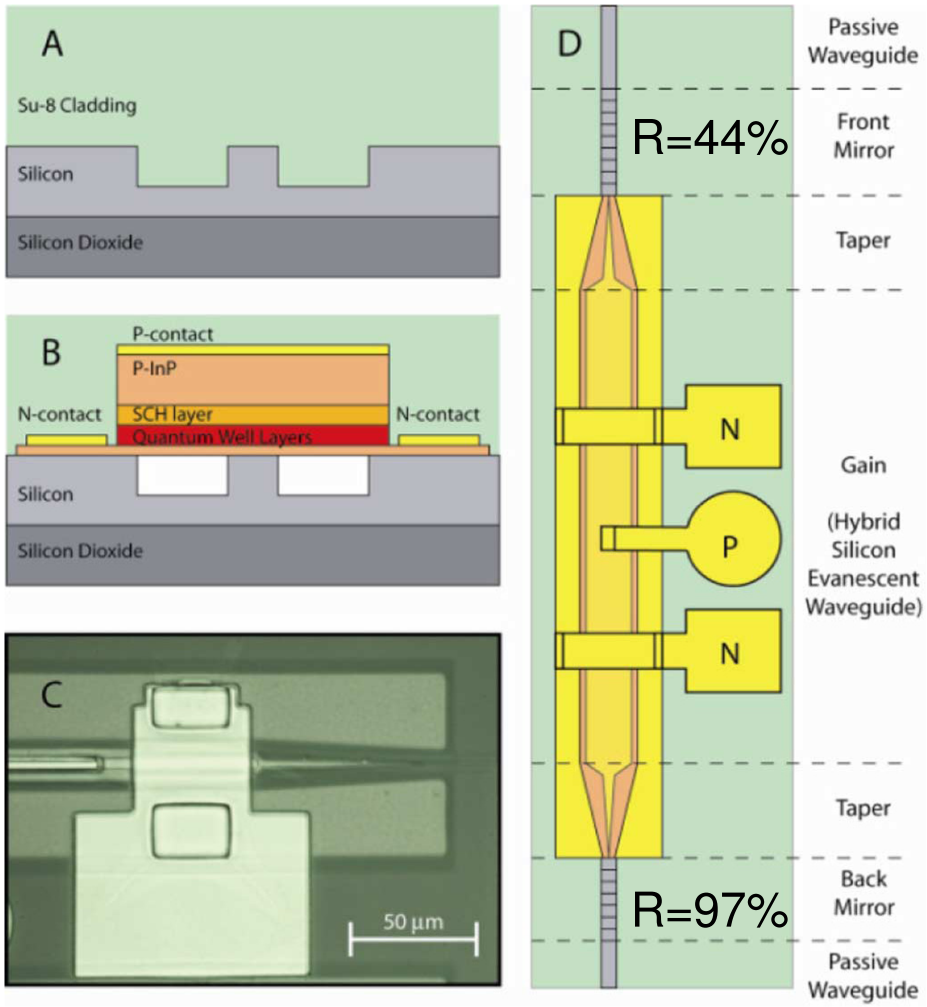
A. W. Fang *et al.* Opt. Express (2008).

- 200um gain section + 2 x 80um **III-V** taper
- Confinement factors:
  - Γ_{QWs}=5.2%
  - Γ_{Si}=59.2%
- → k=240cm^{-1} (index perturbation is located near the center of the optical mode)



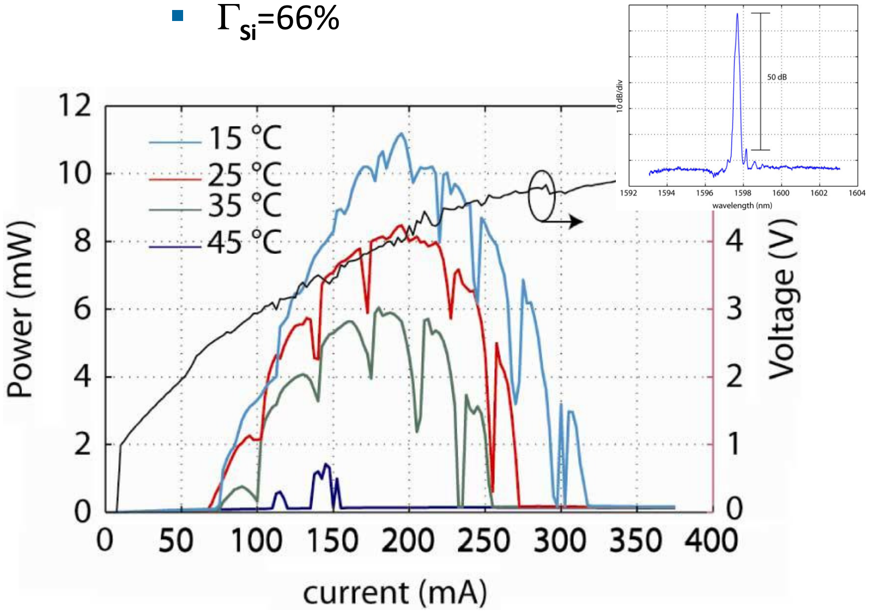
- I_{th} =25mA, P_{max} >4mW @ 10°C
  (Output power measured from both sides)
- SMSR=50dB

DBR lasers



A. W. Fang *et al.* IEEE PTL(2008).

- 400um gain section + 2 x 80um **III-V** taper
- Confinement factors:
  - Γ_{QWs}=4.4%
  - Γ_{Si}=66%



- Mode hoping
- I_{th} =65mA, P_{max} ~11mW @ 15°C (integrating sphere at the front mirror)
- SMSR=50dB
- DML: Modulation bandwidth~3GHz

Heterogeneous integration options

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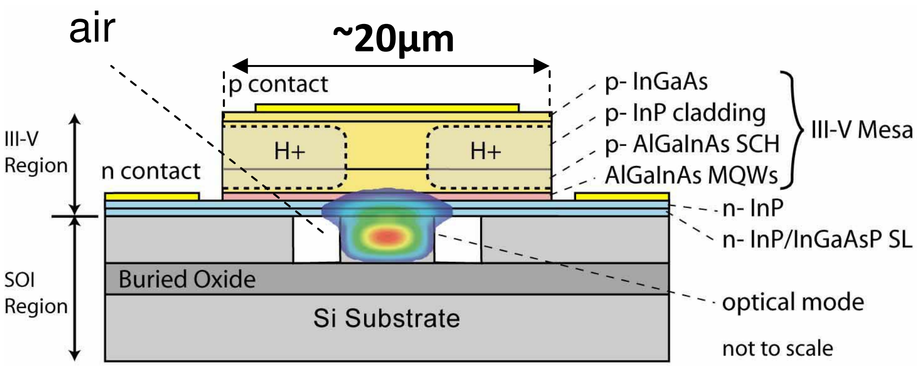

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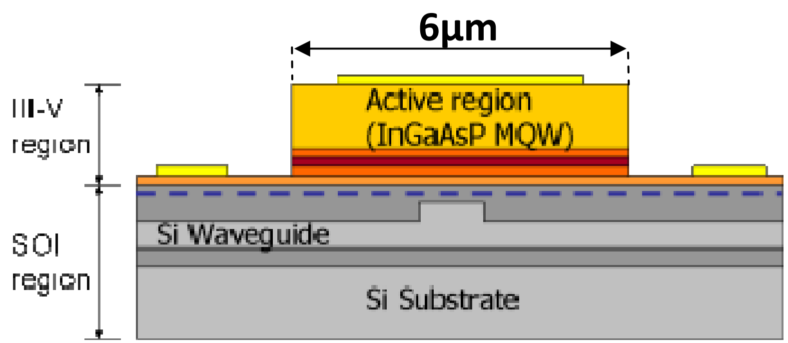

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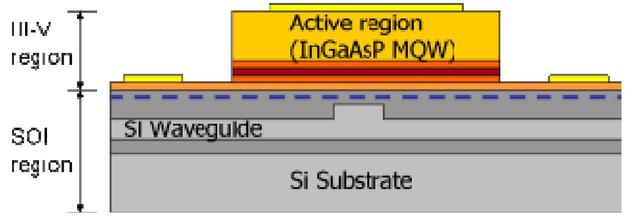
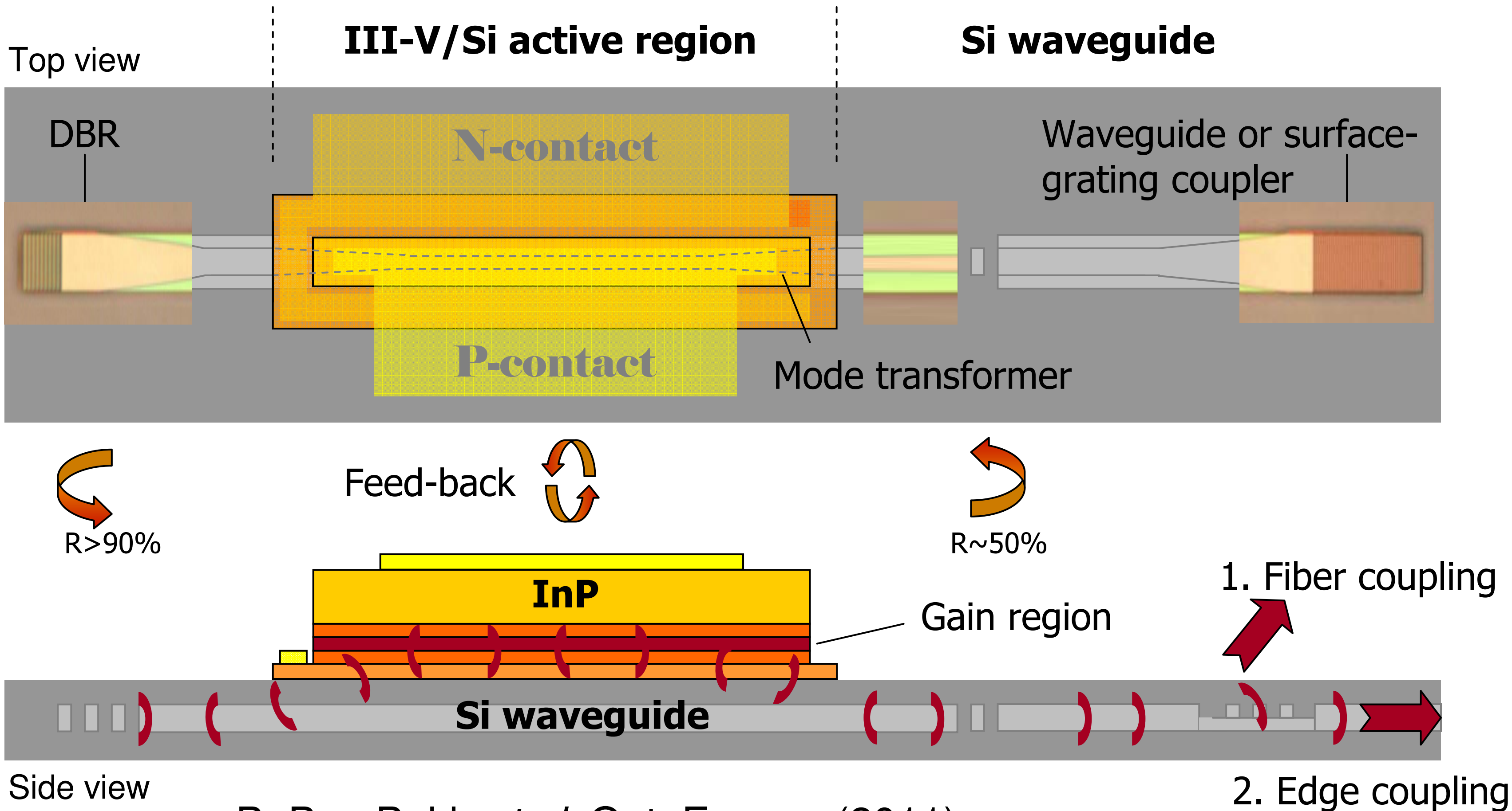
LETI (molecular bonding)
IMEC (Polymer bonding)

Architecture

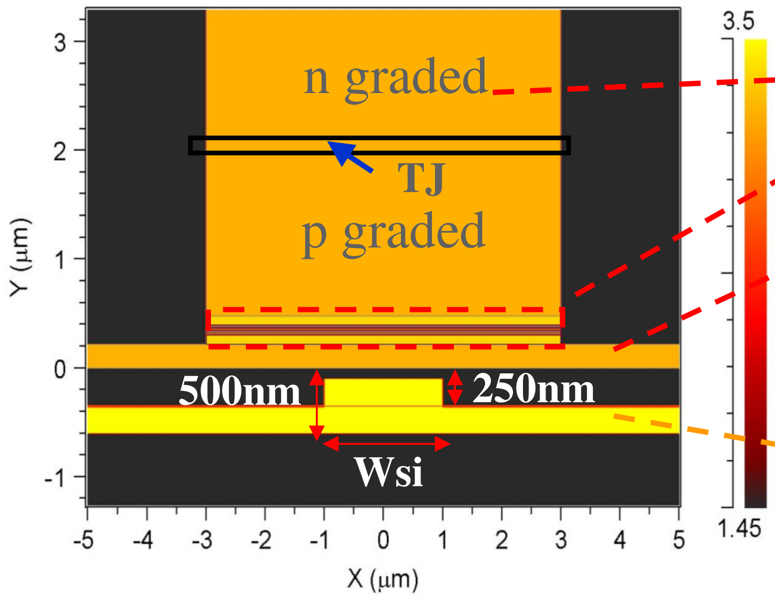
- Gain→ III-V active waveguide
- Si-circuit supports all optical functions





B. Ben Bakir *et al.* Opt. Express(2011)

Adiabatic transition III-V → Si



n/p++/p doped epilayers stack (p-contact)

Active region (MQW=InAsP)

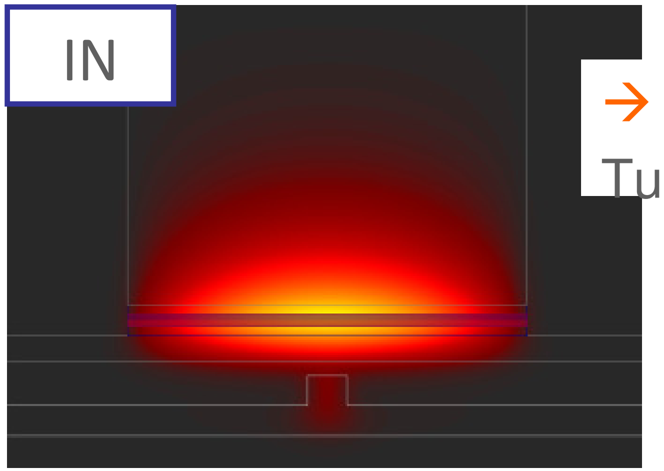
n-doped layer (n-contact)

SiO_2 GAP = 100nm (+-20nm)

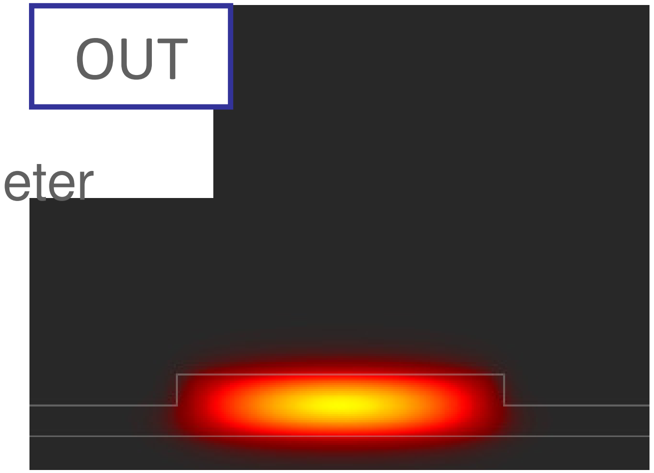
Silicon rib waveguide

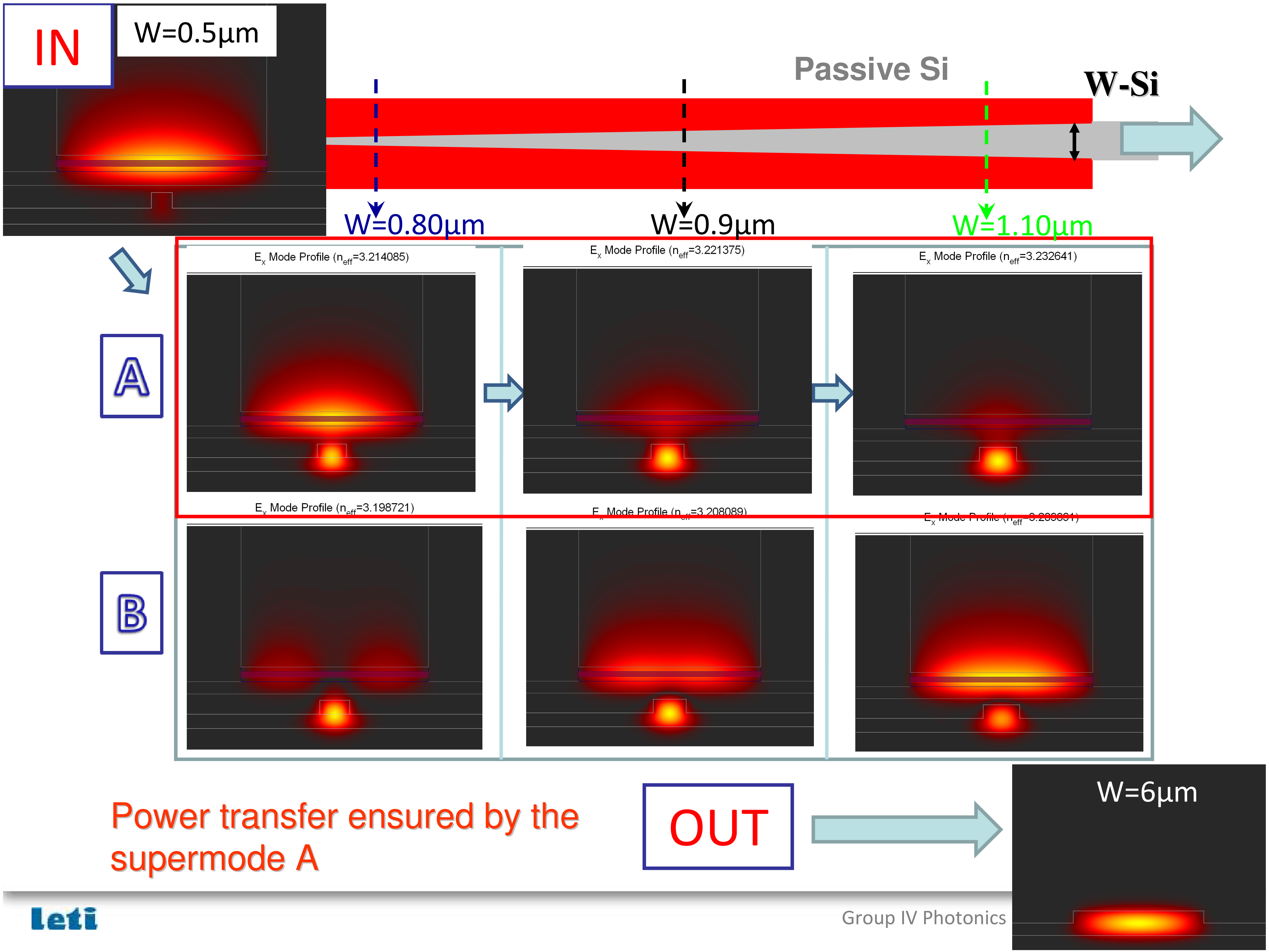
III-V heterostructure: inl

- Mode transformation:



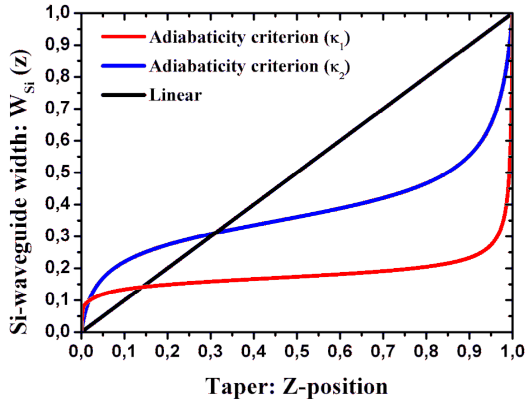
→ W-Si:
Tuning parameter




IN
W=0.5µm
Passive Si
W-Si
W=0.80µm
W=0.9µm
W=1.10µm
Ex Mode Profile (neff=3.214085)
Ex Mode Profile (neff=3.221375)
Ex Mode Profile (neff=3.232641)
A
Ex Mode Profile (neff=3.198721)
Ex Mode Profile (neff=3.208089)
B
Power transfer ensured by the supermode A
OUT
W=6µm

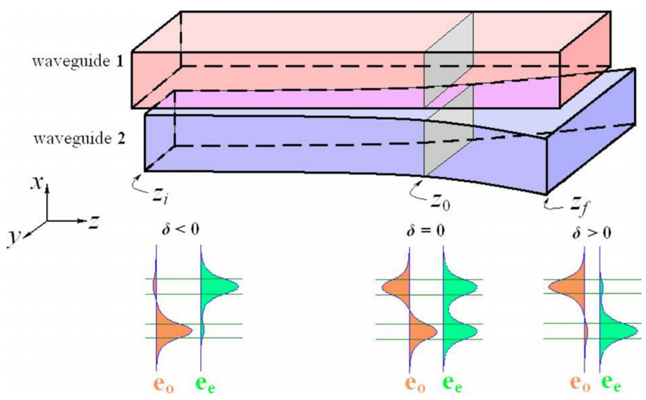
Adiabaticity criterion

- Universal criterion for designing adiabatic mode transformers
  - Criterion relates ε
  - The shortest possible length of an adiabatic mode transformer
  - Taper shape:



$$\begin{cases} W_{Si}(z) = f(\gamma(z)) \\ \gamma(z) = \dfrac{\delta(z)}{\kappa_{z_0}} = \tan\left[\arcsin\left(2\kappa_{z_0}\,\varepsilon^{1/2}(z - z_0)\right)\right] \end{cases}$$

- δ: mismatch of propagation constants between the individual uncoupled waveguide modes
- z_0: phase matching point (δ=0)
- κ_{z0}: coupling strength between waveguides at the phase matching point
- ε: fraction of power scattered in the unwanted supermode (odd mode)

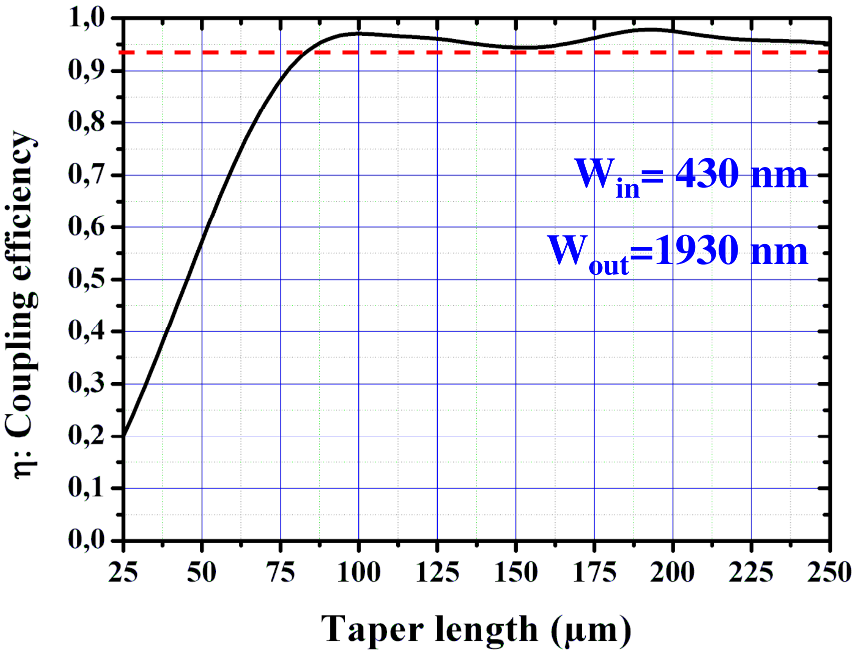


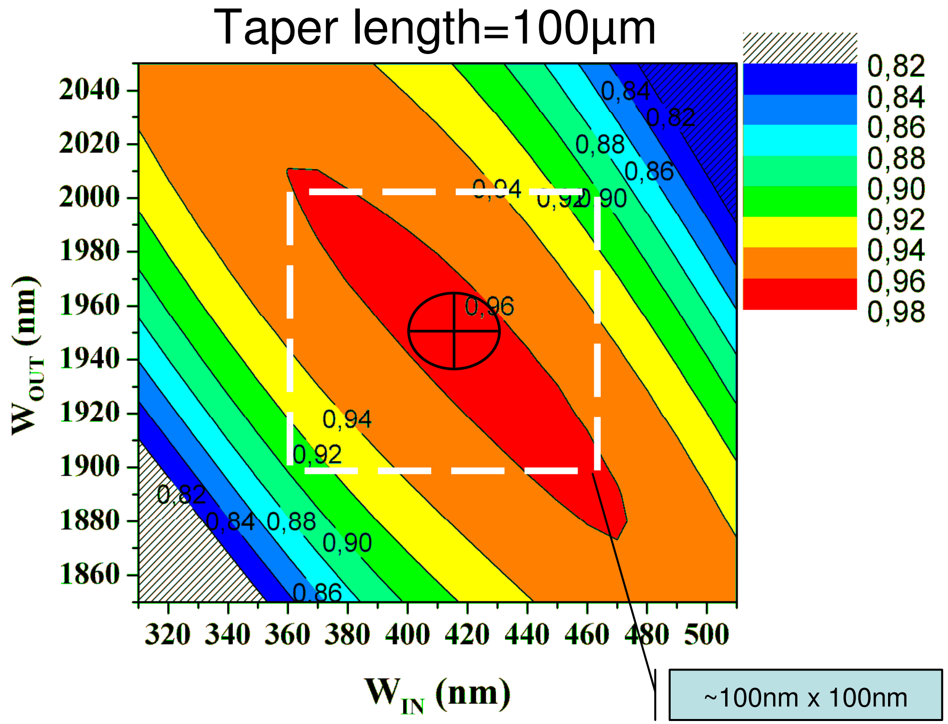
X. Sun, H.-C. Liu, and A. Yariv, Opt. Lett., 34, 280-282 (2009).

γ(z)-shaped adiabatic taper

- ε~2%, Lc_{min}=100µm
- Taper length >80µm:
  - η>94%

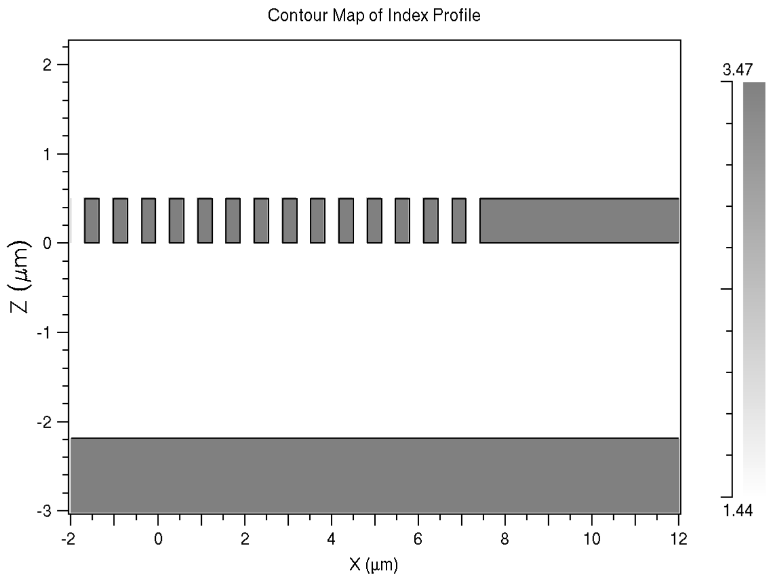
- Robust design:
  - Lc=100µm:
  - $\Delta W_{Si} = \pm 50nm$ → η>90%

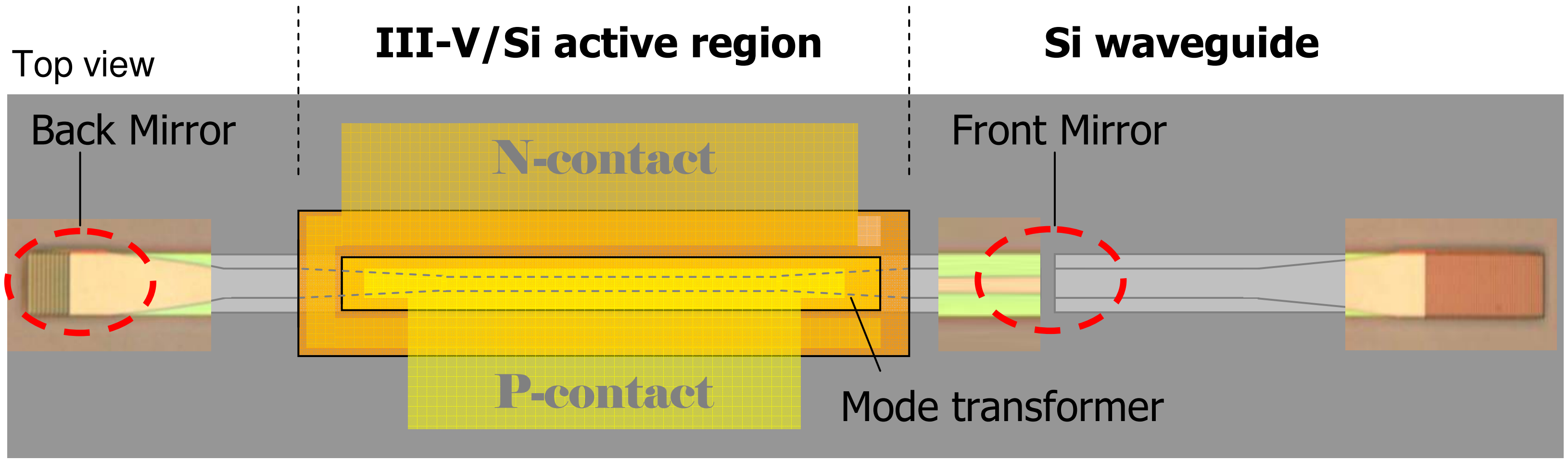




F-P cavity: broadband DBRs

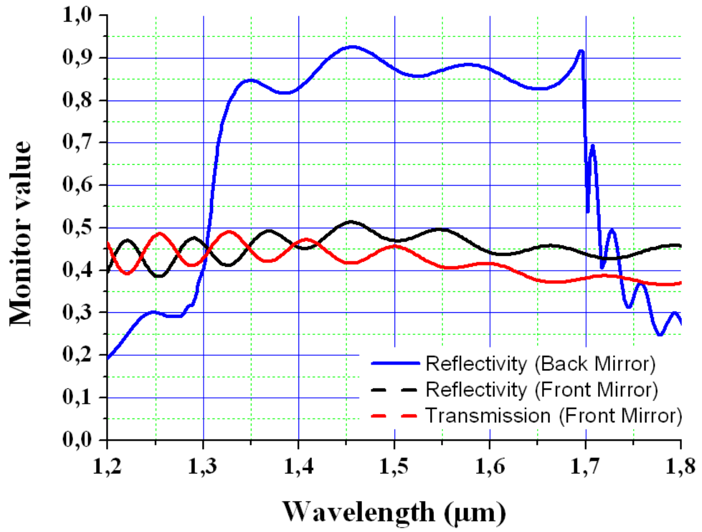
- Period=650nm
- Etch depth=500nm
- Grating length
  - Back mirror=6.5µm
  - Front mirror= 1 slit (0.325µm)

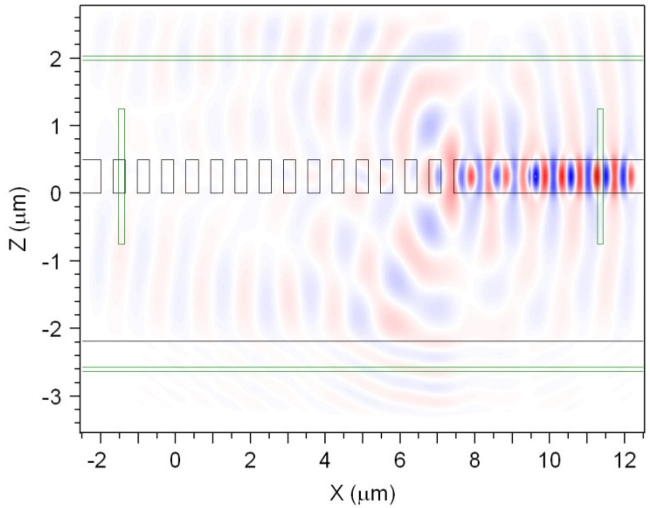


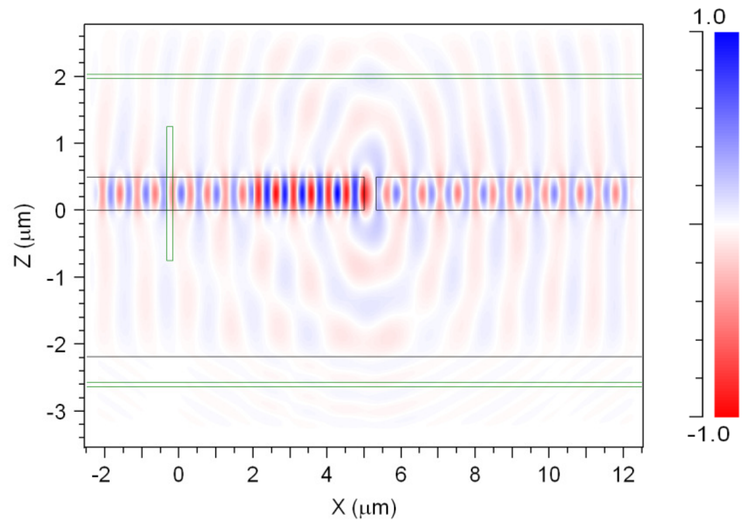


F-P cavity: broadband DBRs

- Back mirror:
  - R~90%
  - Δλ >300nm
- Front mirror:
  - R~50%
  - T~40%

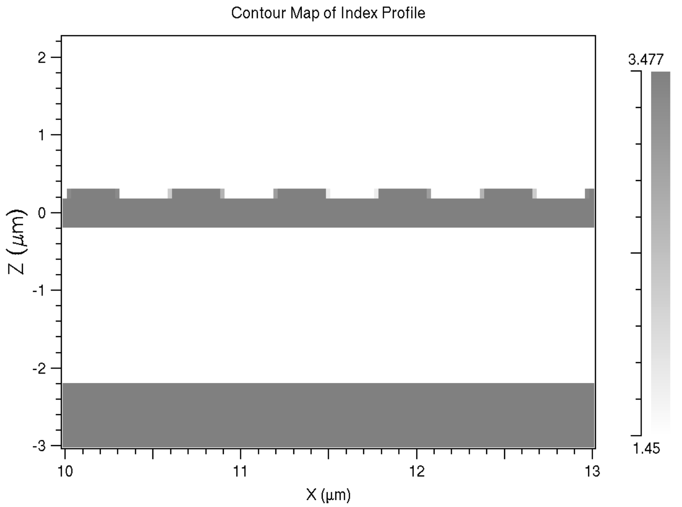


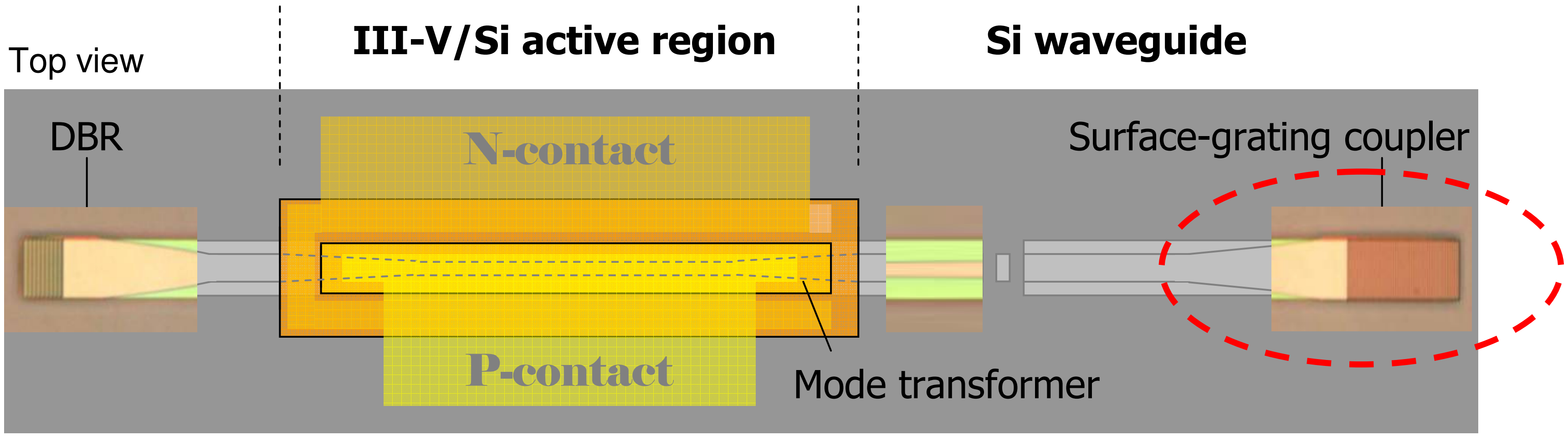




Fiber-coupler

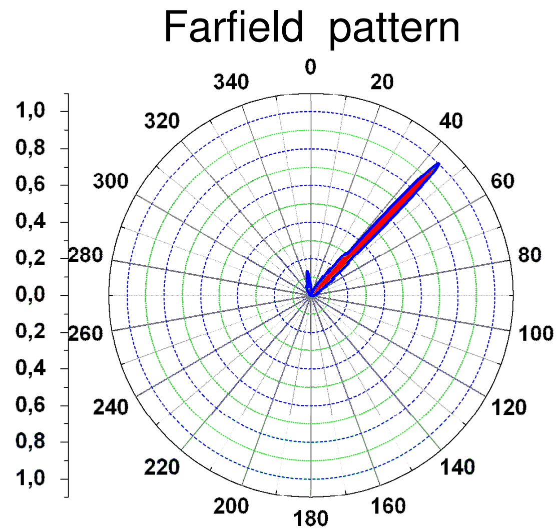
- Period=590nm
- Etch depth= 125nm

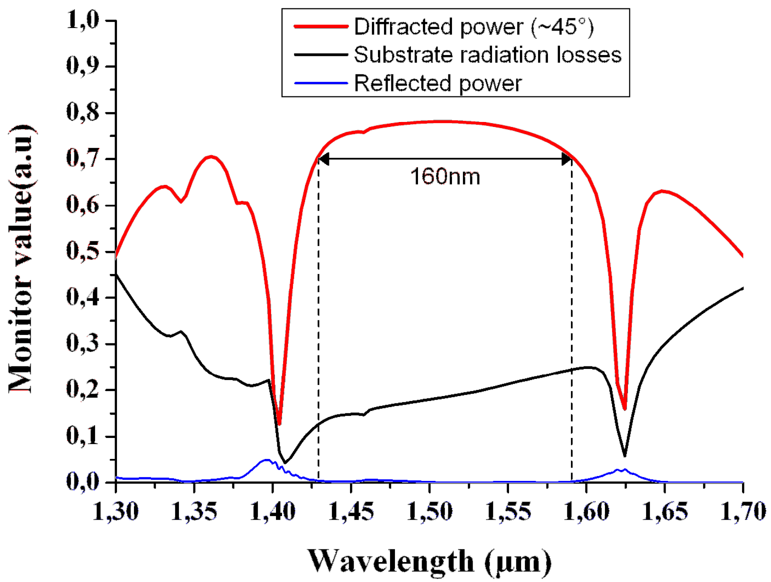


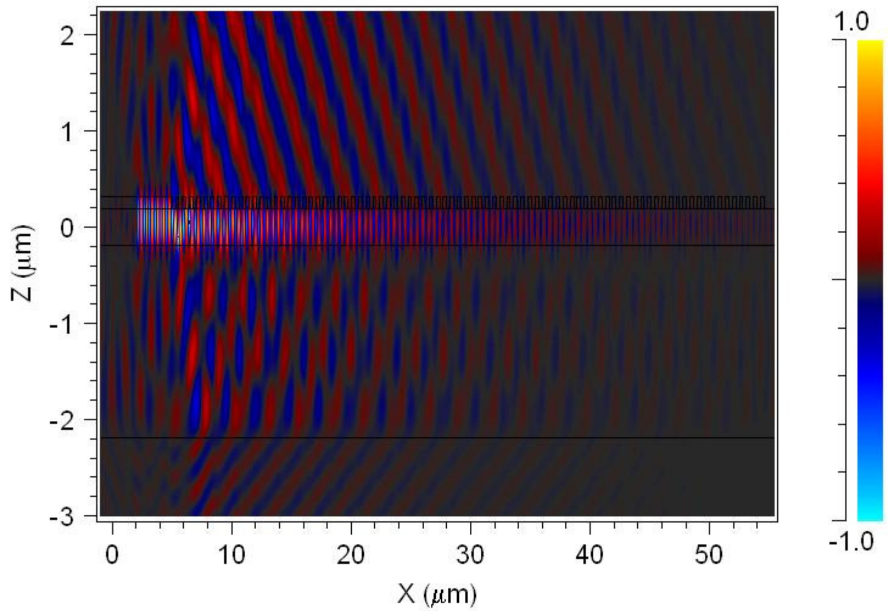


Fiber-coupler

- Upwards radiated power
  - R_P>70%, $\Delta\lambda$ >160nm
  - θ=45°
- Coupling to MMF ~60%





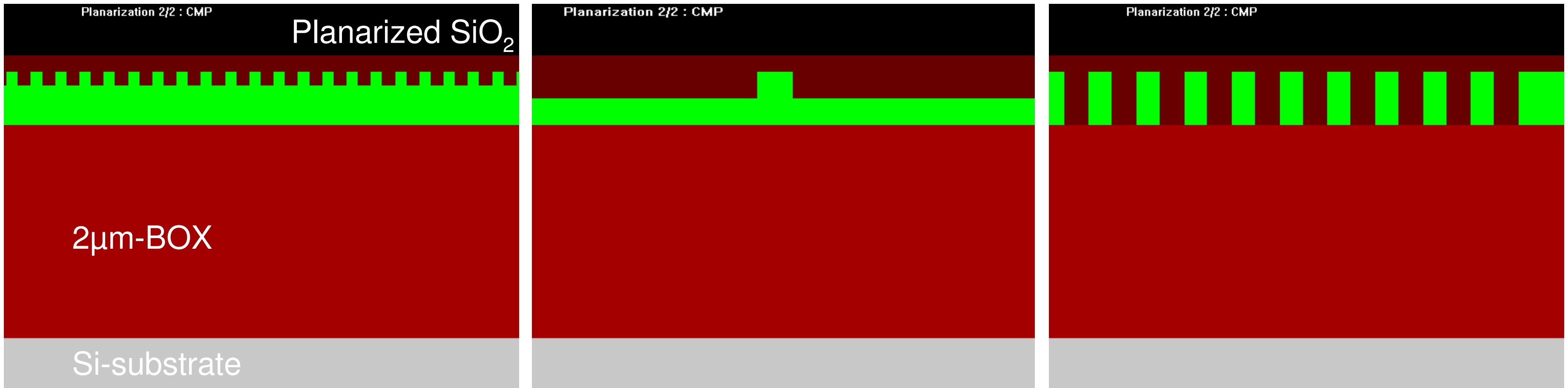


Si-waveguide fabrication

200mm SOI wafer: 500nm-Si / 2µm-BOX

- Surface grating coupler: hard mask/litho/partial etching (125nm)/stripping
- Waveguides and tapers: hard mask/litho/partial etching (250nm)/stripping
- Mesas + Bragg reflectors: hard mask/litho/full etching (500nm)/stripping
- SiO2 encapsulation and planarization by CMP (100nm)

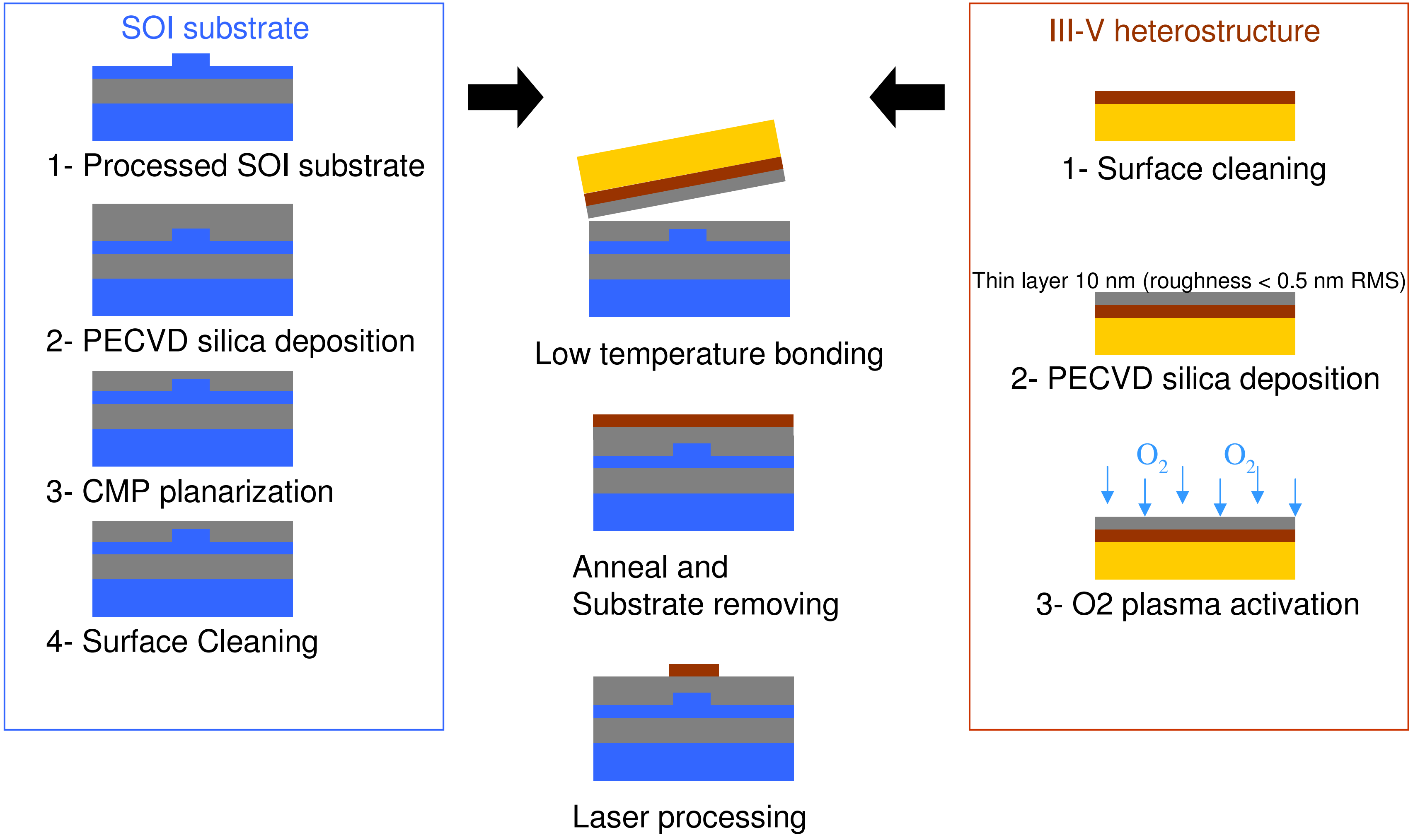
Surface-grating coupler | Mode transformer (cross-section) | Bragg reflector



Integration

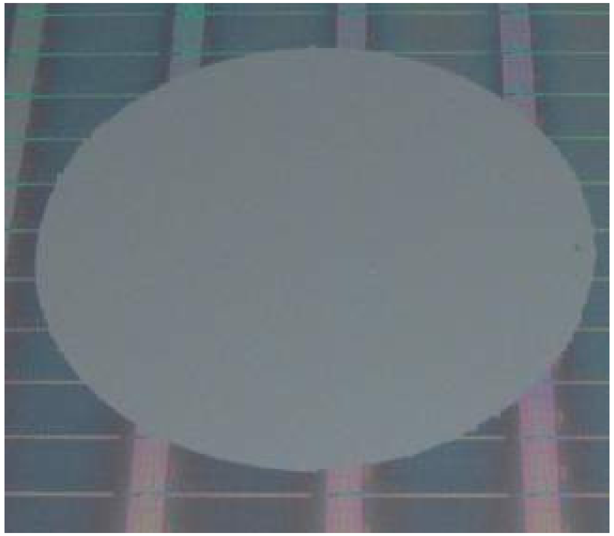
- Wafer-to-wafer bonding
- Die-to-wafer bonding
- Die-to-wafer bonding (with a support handle)
- Hybrid SiO_2/Polymer bonding

Molecular bonding

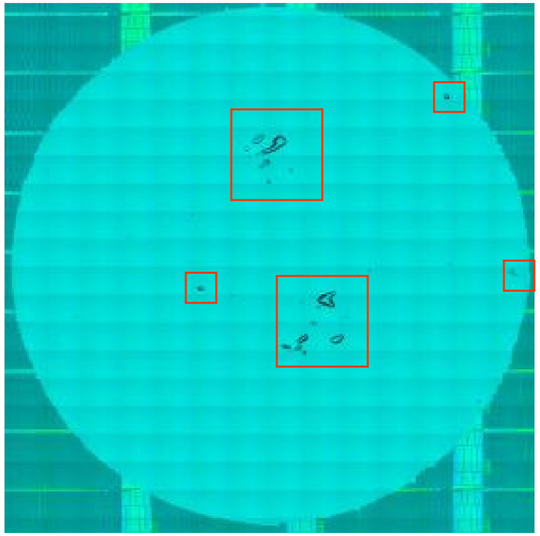


Wafer-to-wafer bonding

- 2'' InP wafer(100nm thick SiO_2 spacing layer)
- Epilayer heterostructure of 3µm-thick
- Bonding yield of 95%

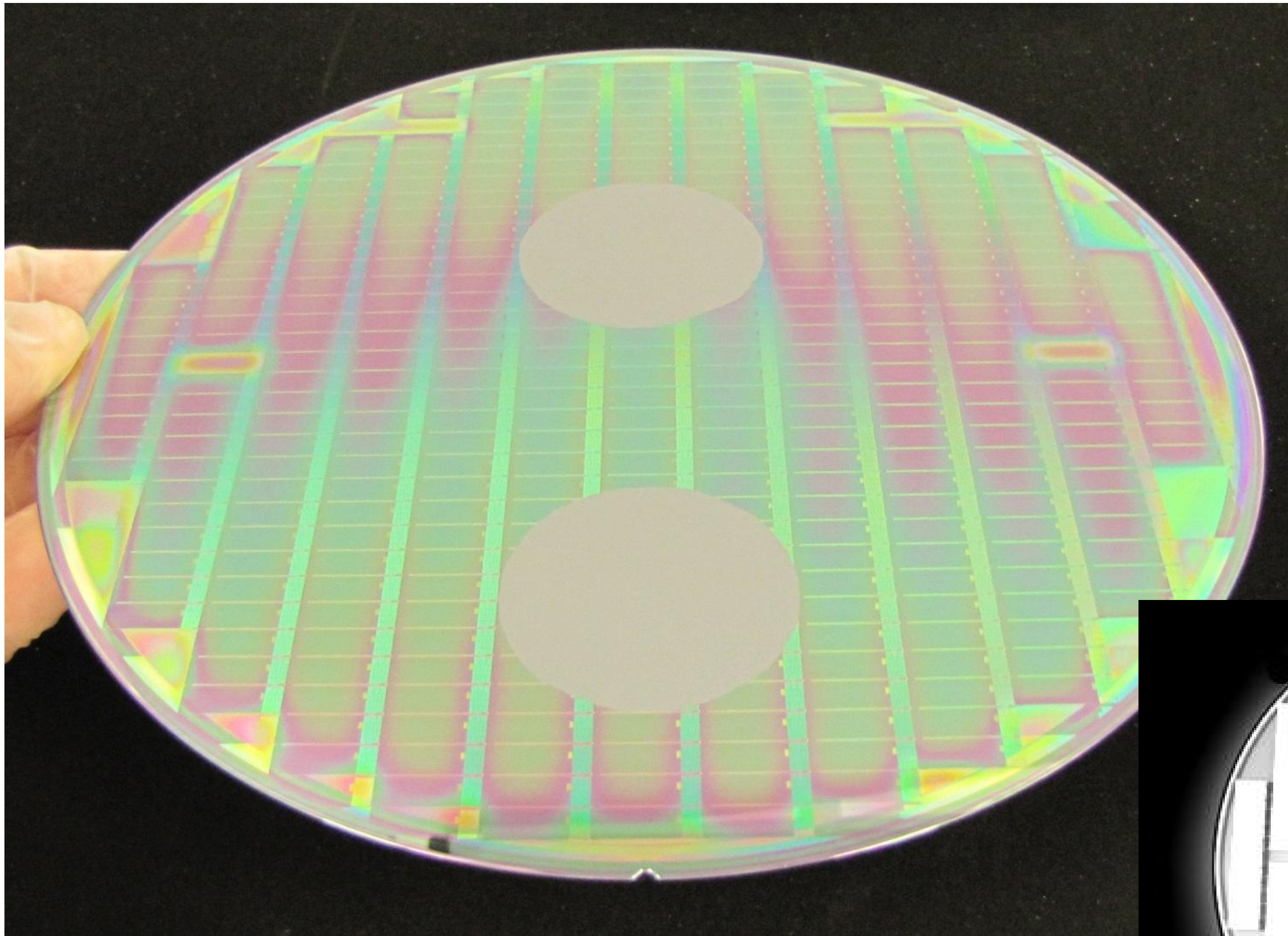


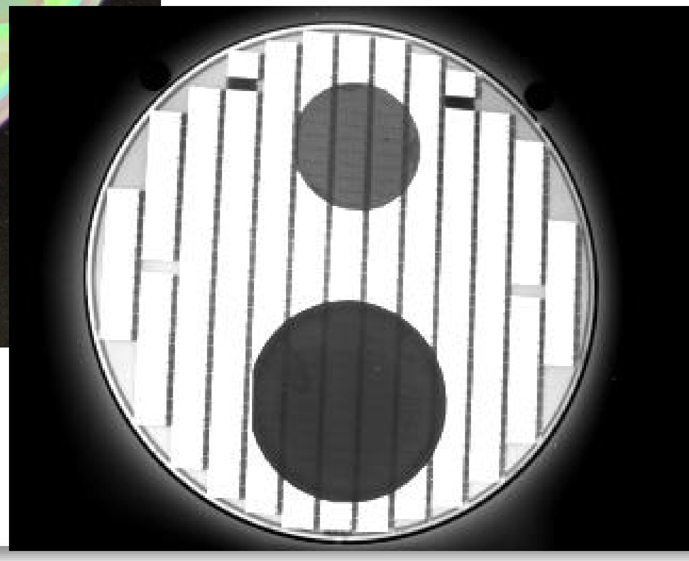
2'' InP heterostructure bonded on processed SOI after substrate removal



Optical microscope image (automatic stitching) showing interfacial defects

Wafer-to-wafer bonding



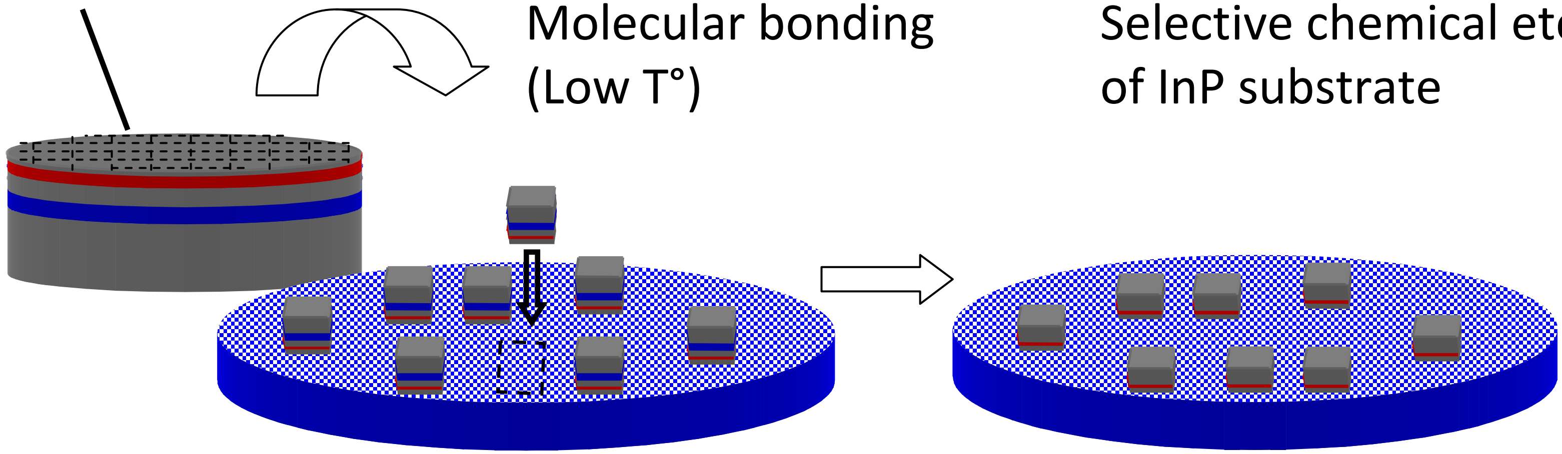


Die-to-wafer bonding

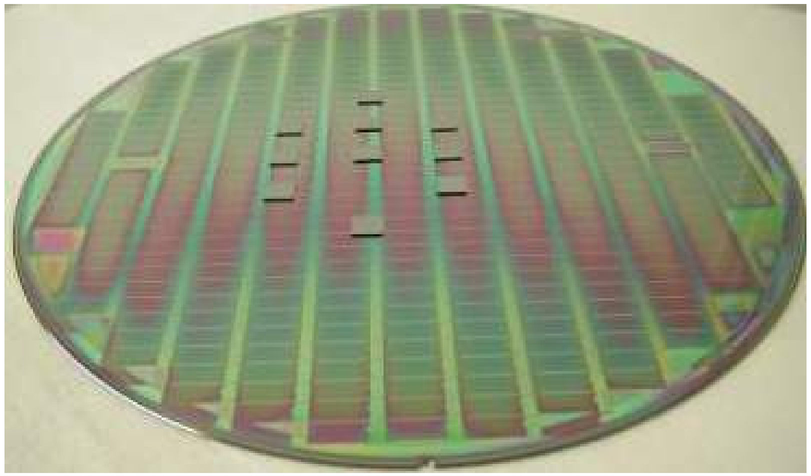
Dicing InP wafer

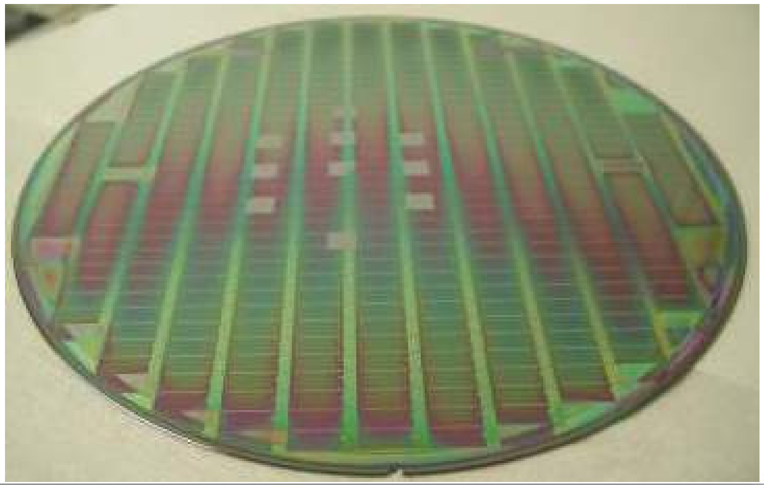
Molecular bonding (Low T°)

Selective chemical etching of InP substrate



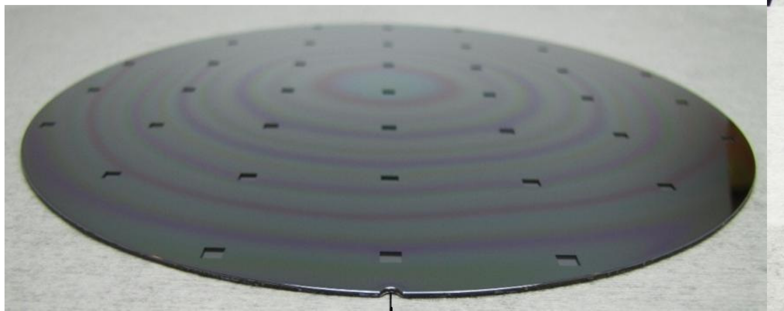
Bonding yield > 85%



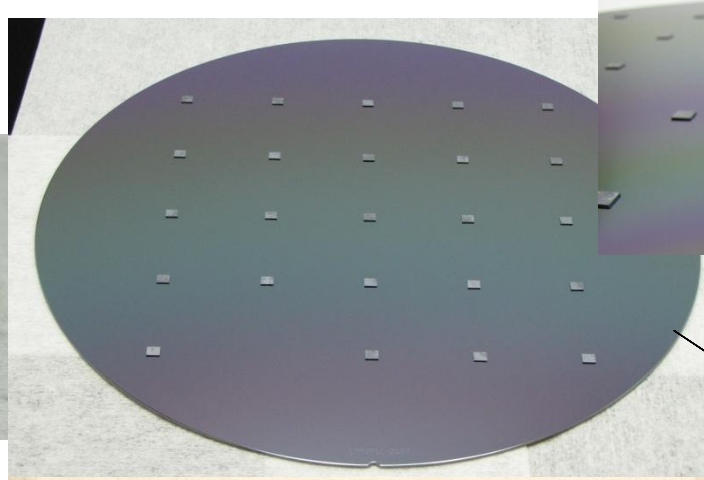


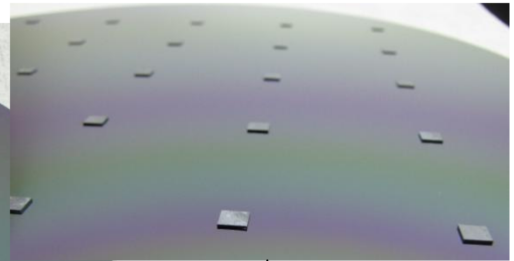
Die-to-wafer bonding (support handle)

- Use of support handle
  - **Collective process**
  - **Possibility of precise alignment**
  - High yield (>80%)
  - →Under optimization

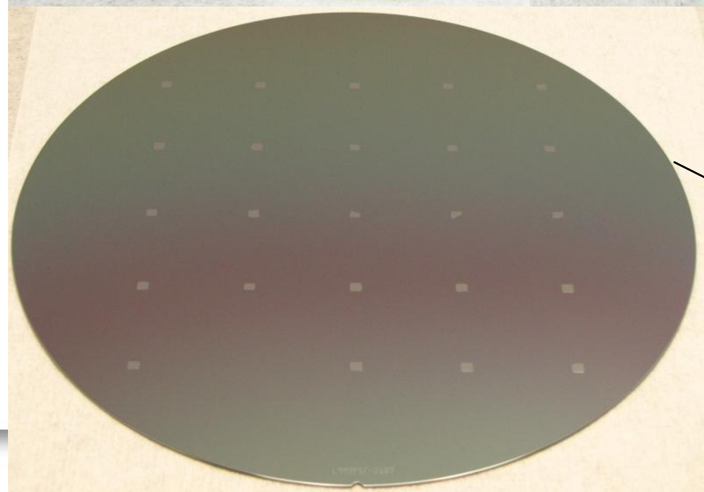


Support handle wafer
with predefined places



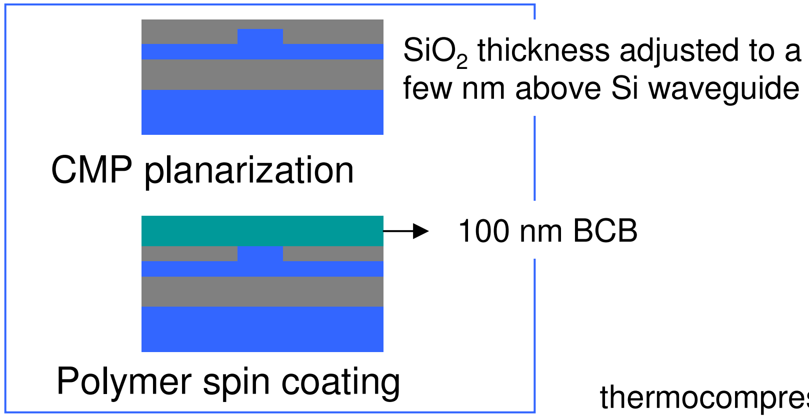


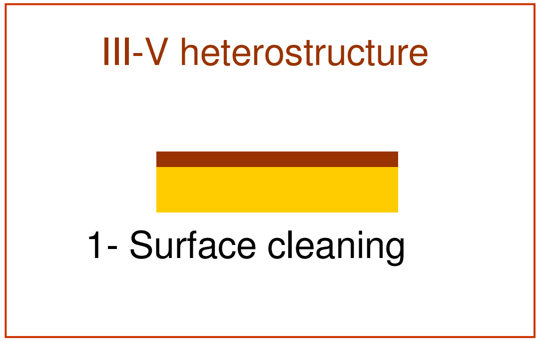
III-V dies bonded on Si

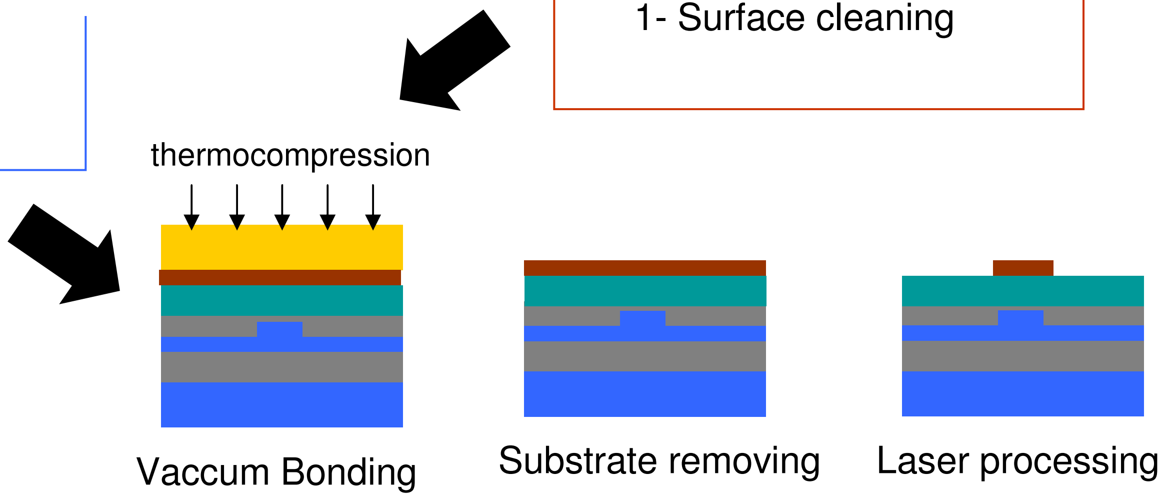


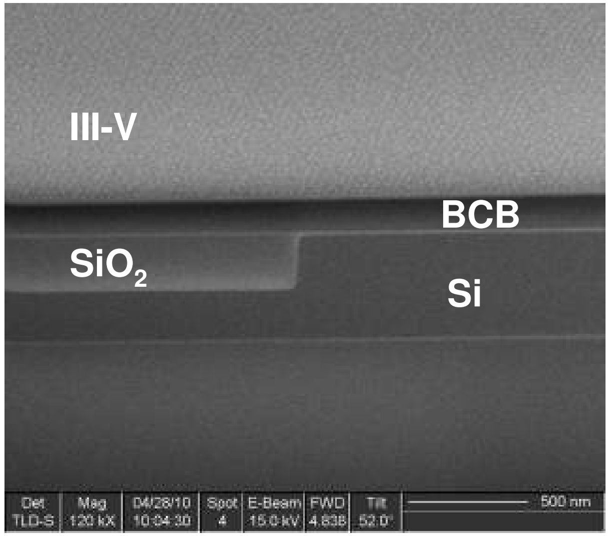
III-V dies bonded on Si after InP substrate removal

Polymer bonding







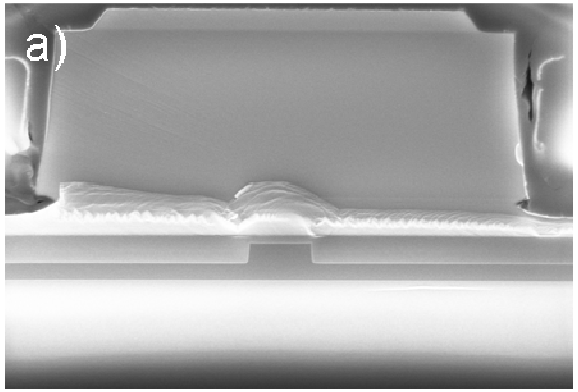


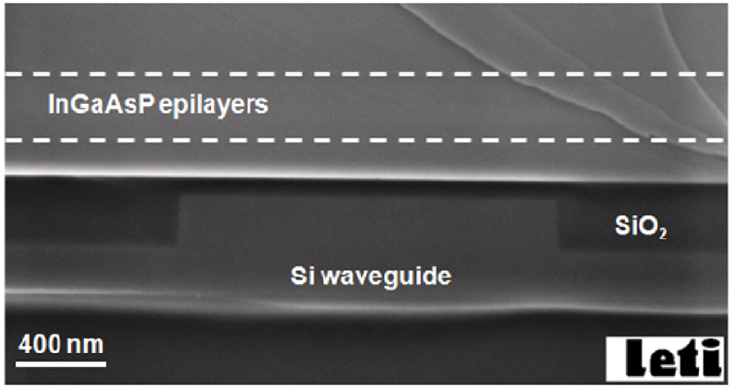
SEM cross sectional image of III-V structure bonded above Si waveguide with BCB

- Polymer bonding:
  - less depending on surface preparation, roughness , defects
- BCB: refractive index 1.54 @1.55µm ~ SiO2
- Bonding yield of 80%

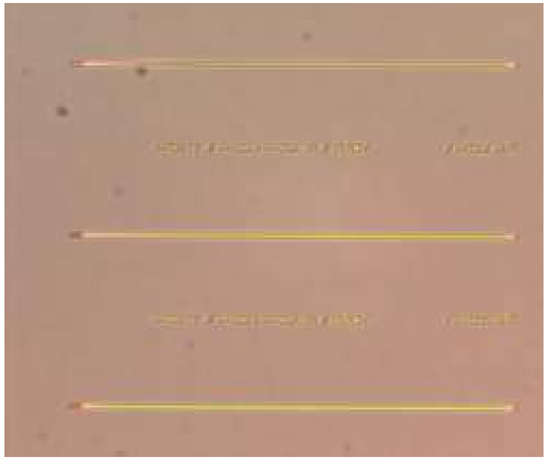
III-V waveguide definition

- Partial dry etching: RIE CH4/H2

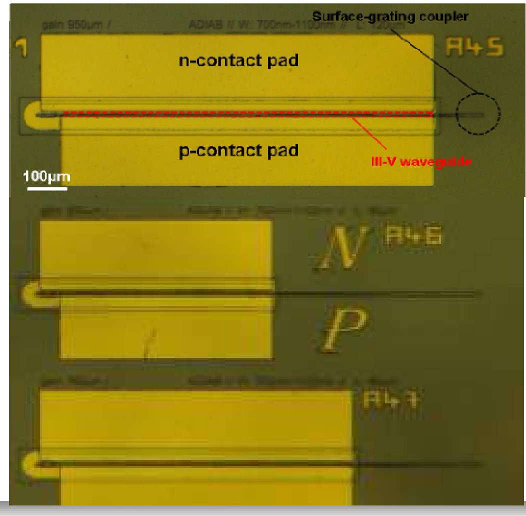




- Si circuits



- After bonding/metallization

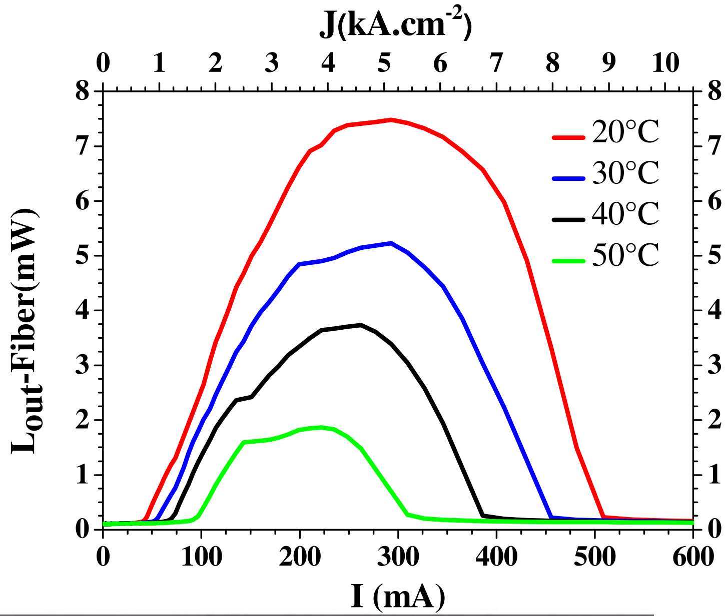


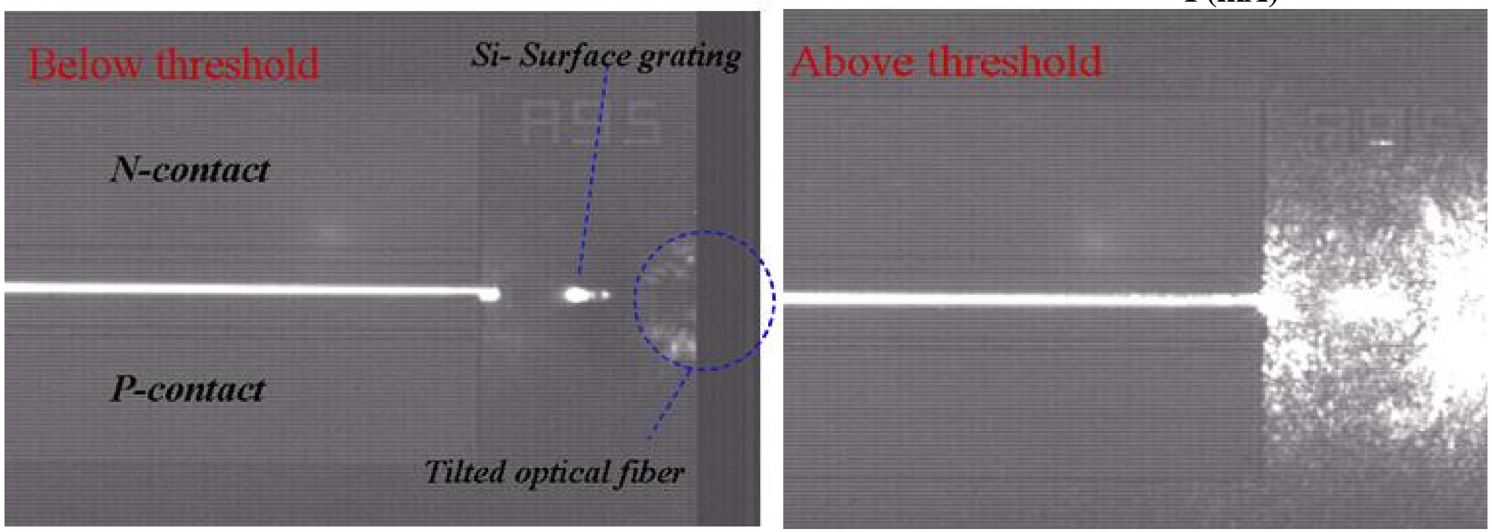
Ni/AuGe/Ni/Au:

Rc < 10^{-6} Ω.cm-^{2}

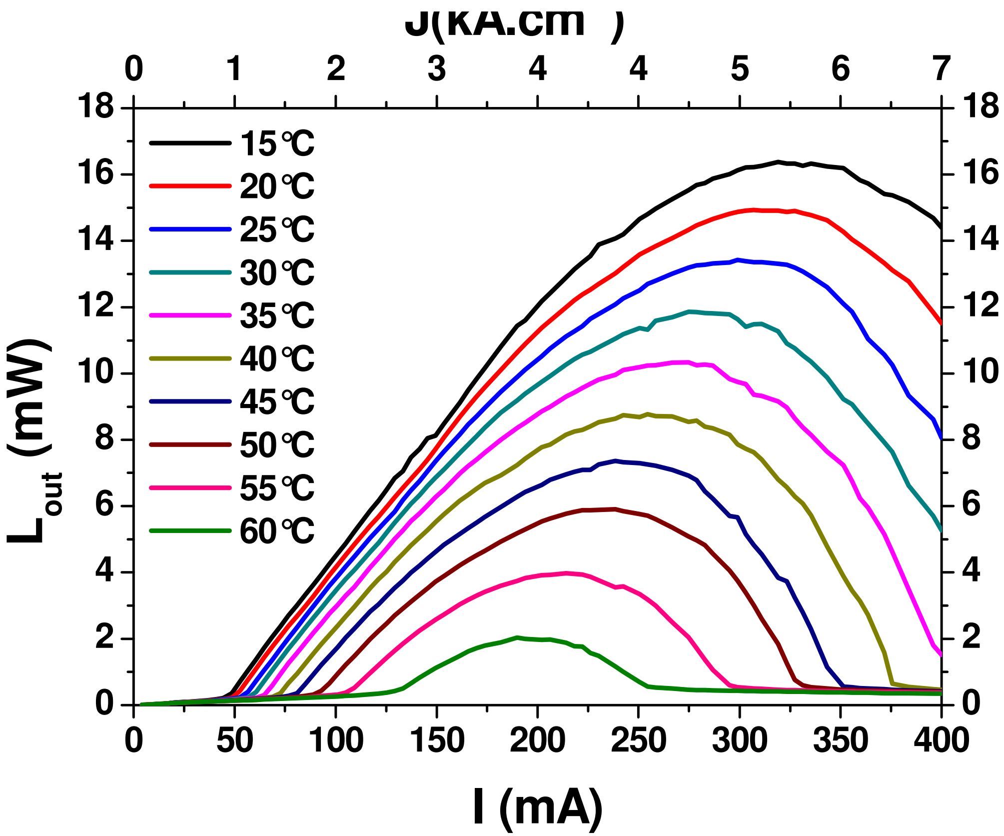
Hybrid F-P laser: Experimental results

- CW operation (>50°C) @ λ = 1.59µm
- I_{th}: 40 -100mA (1-2 $kA.cm^{-2}$)
  - for T: 20 à 50°C
- $\mathscr{P}_{\_fiber}$ > 7 mW

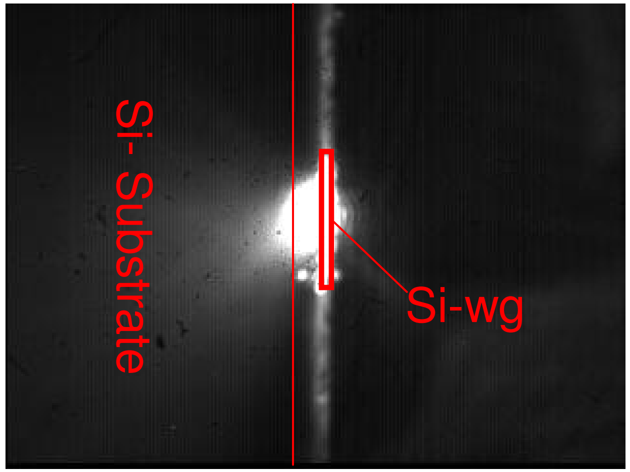




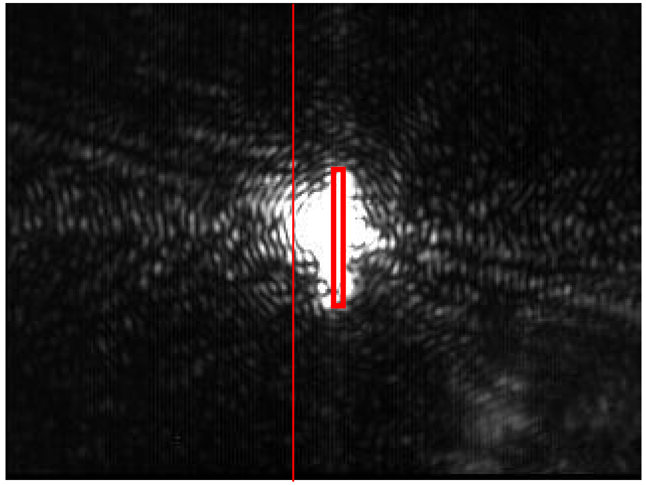
- Integrating sphere
  - Low reflectivity side (front mirror)
  - Pout>16mW @15°C
  - Pout>1.5mW @60°C



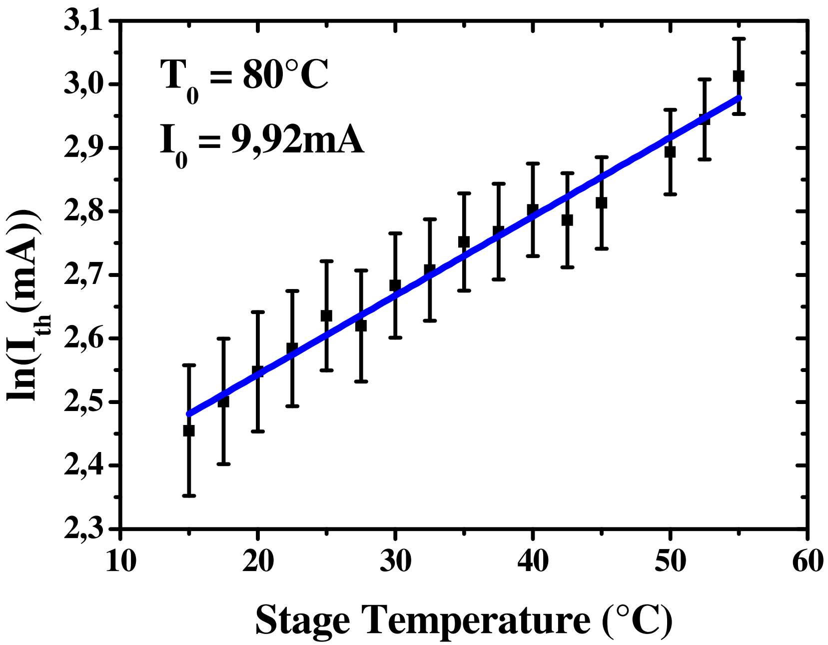
Below threshold

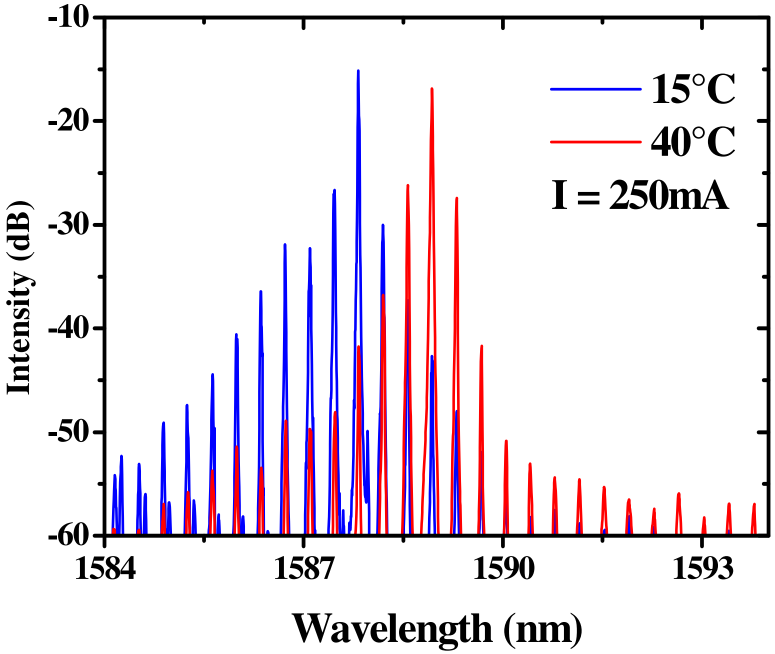


Above threshold



- Temperature dependence of laser threshold current (pulsed) T_0=80°C (I=I_0 exp [T/T_0])
- Temperature dependence of lasing wavelength (CW) dλ/dT=0.045nm/ °C

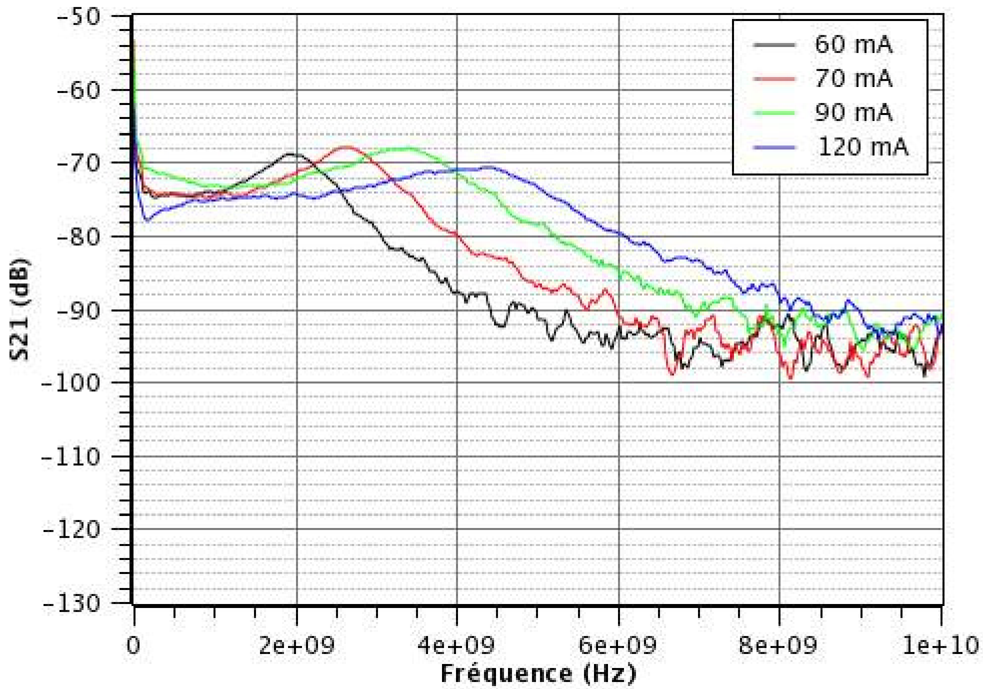




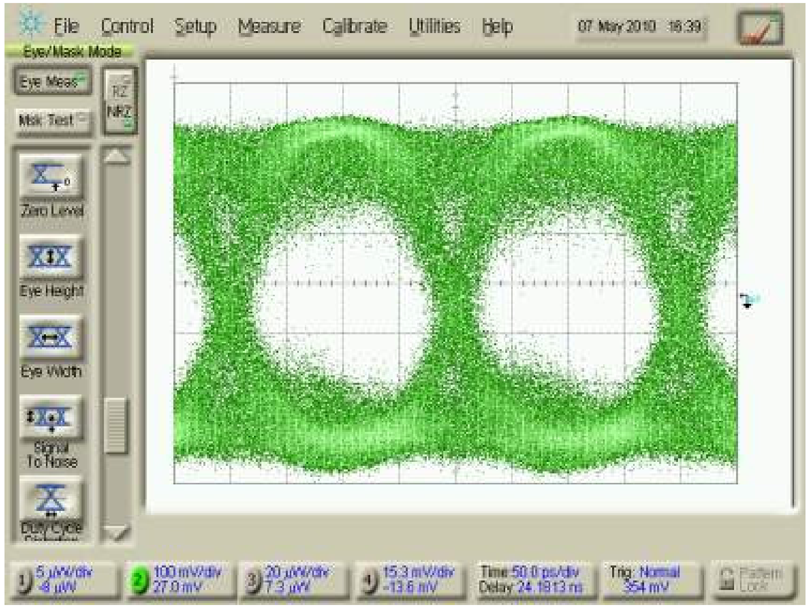
Direct modulation

- Modulation Bandwidth ~6GHz (RT)
- Eye diagram for 5Gb/s modulation: ER~ 4dB

Small signal modulation response

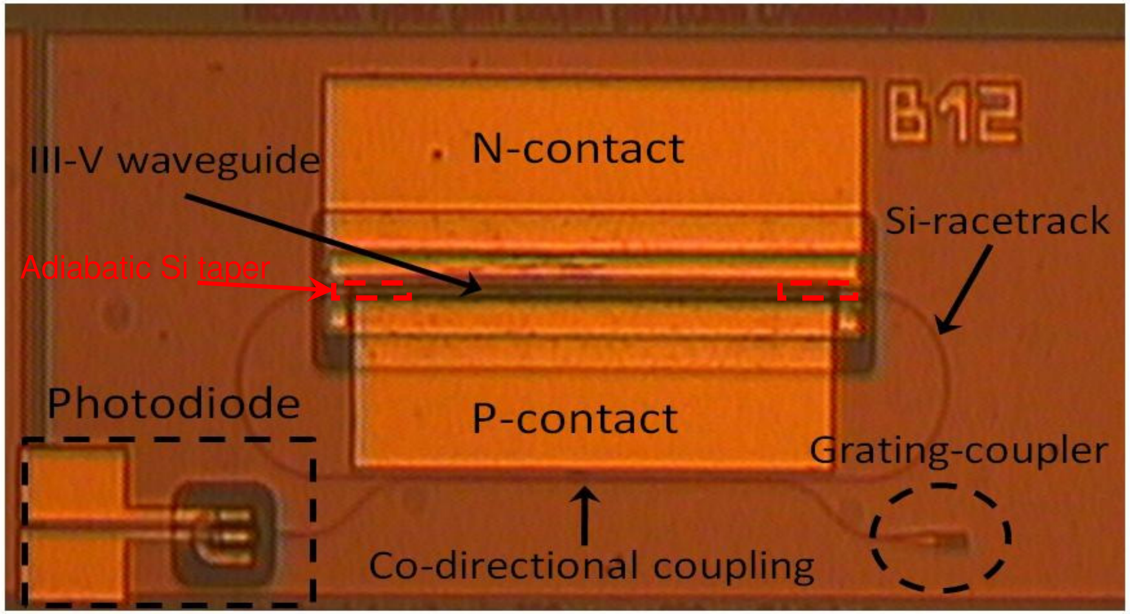


Eye diagram for 5Gb/s modulation



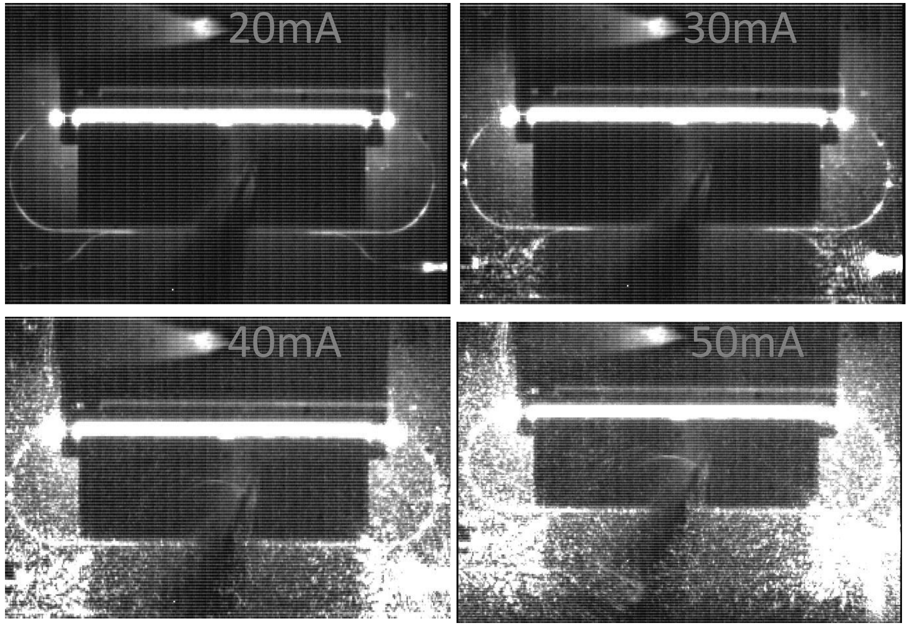
Integrated Si/III-V racetrack laser, photodetector and waveguide-to-fiber surface grating coupler

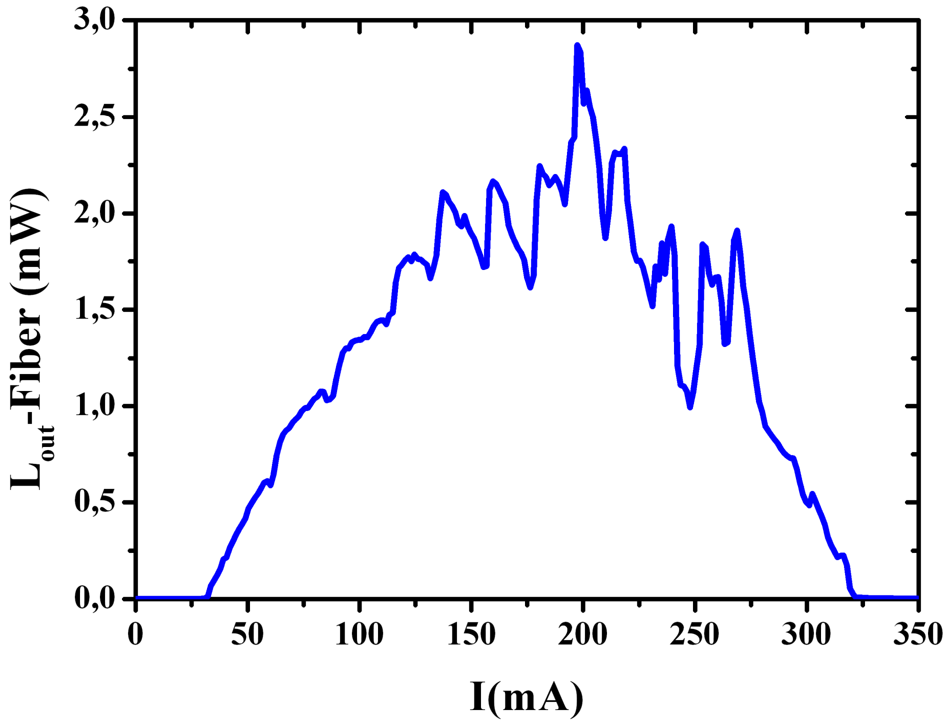
- III-V hterostructure, coupling scheme= F-P laser
- Cavity: Broadband DBRs→ Si racetrack + directional coupler

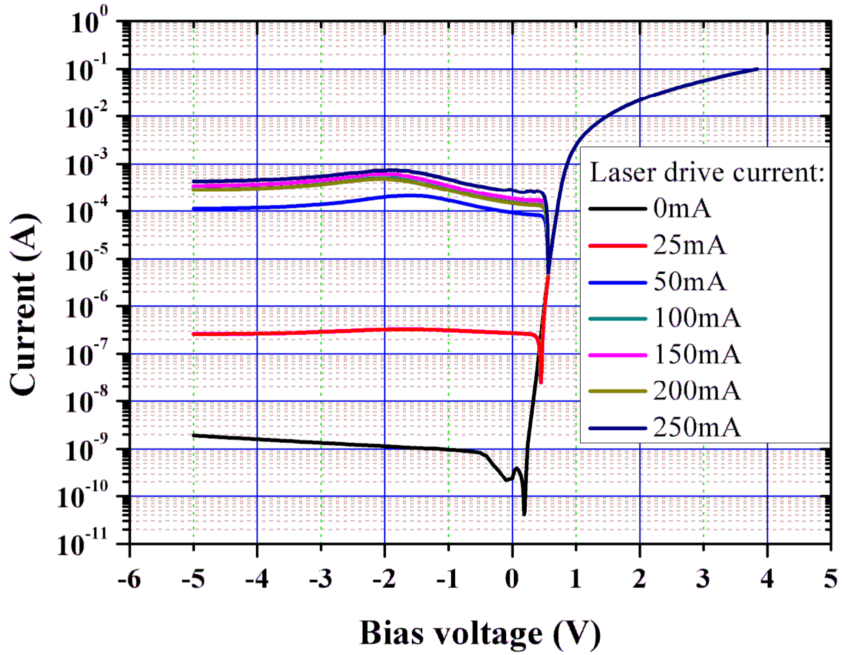


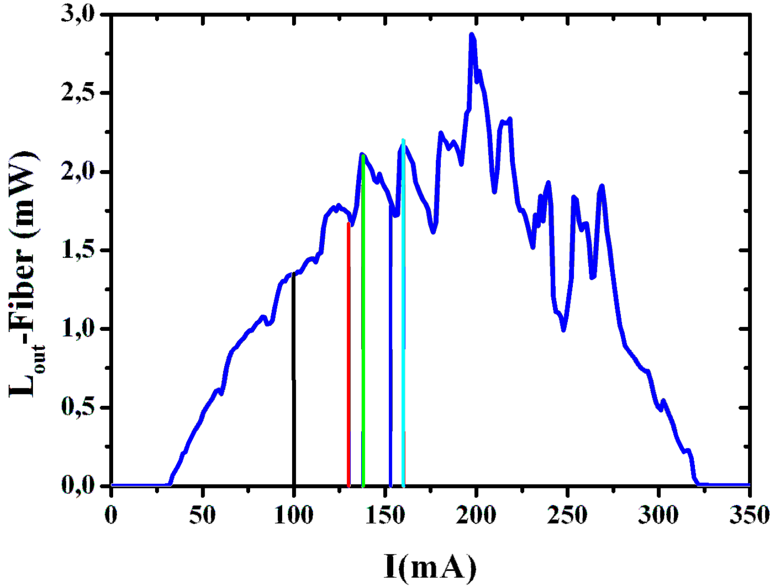
- Photodetector (CW) + Surface grating coupler (CCW) at both ends

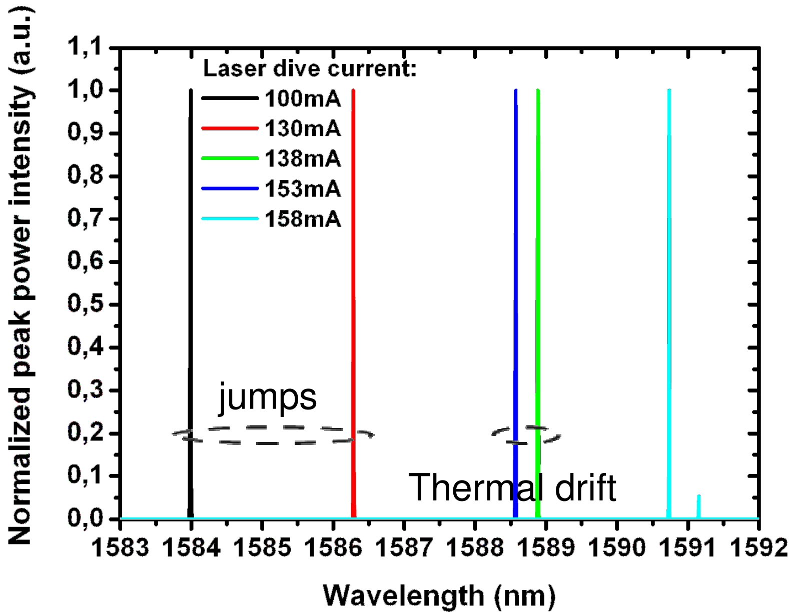
- Laser:
  - CW operation @ RT
  - I_{th}: 30 mA
  - $\mathscr{P}_{\_fiber}$ ~ 3 mW
- Photodetector:
  - I_{dark} ~ 1 nA
  - Max. responsivity @ -2V
    - ~O.3 A/W (coupling not optimized)





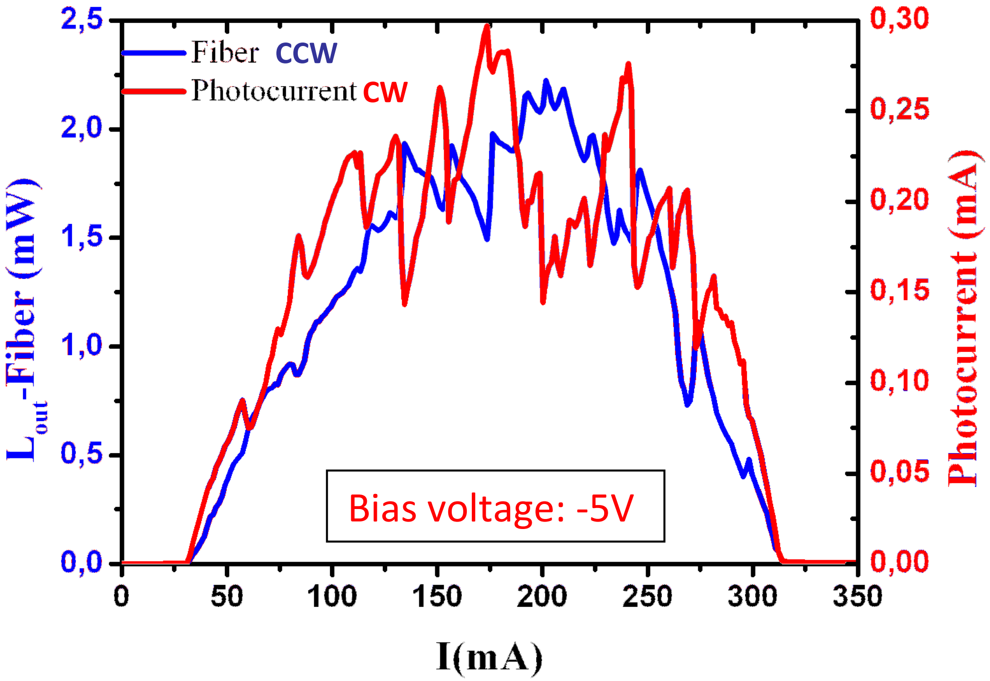






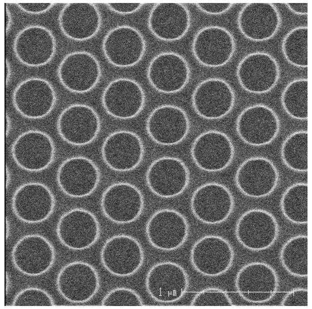
- Kinks in the LI & I_{laser}-$I_{ph.detector}$ characteristics
  - Mode hoping between CW/CCW modes
- Directional “flips”
  - Jumps in the lasing wavelength (2nm)
  - Small thermal drift between switches

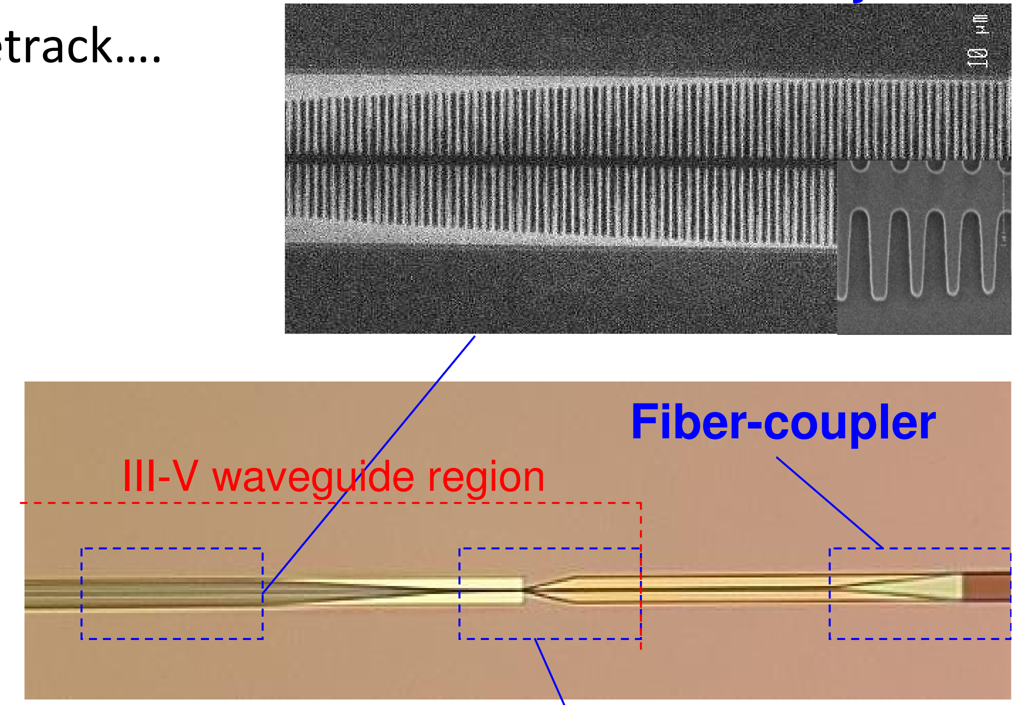
→ External ASE light source for unidirectional lasing

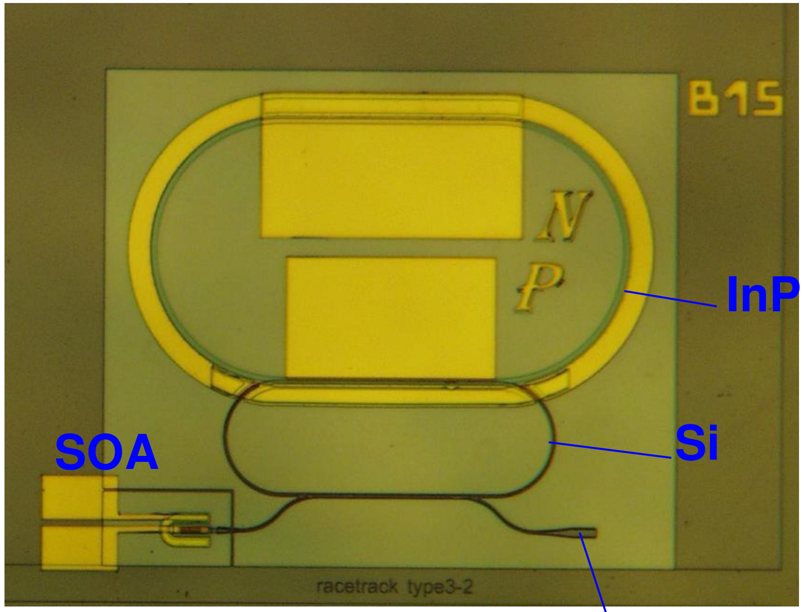


Perspectives

- Exploration of new designs/concepts
  - DFB, narrowband DBRs
  - Slow-wave structures
  - Photonic crystals, double-racetrack….

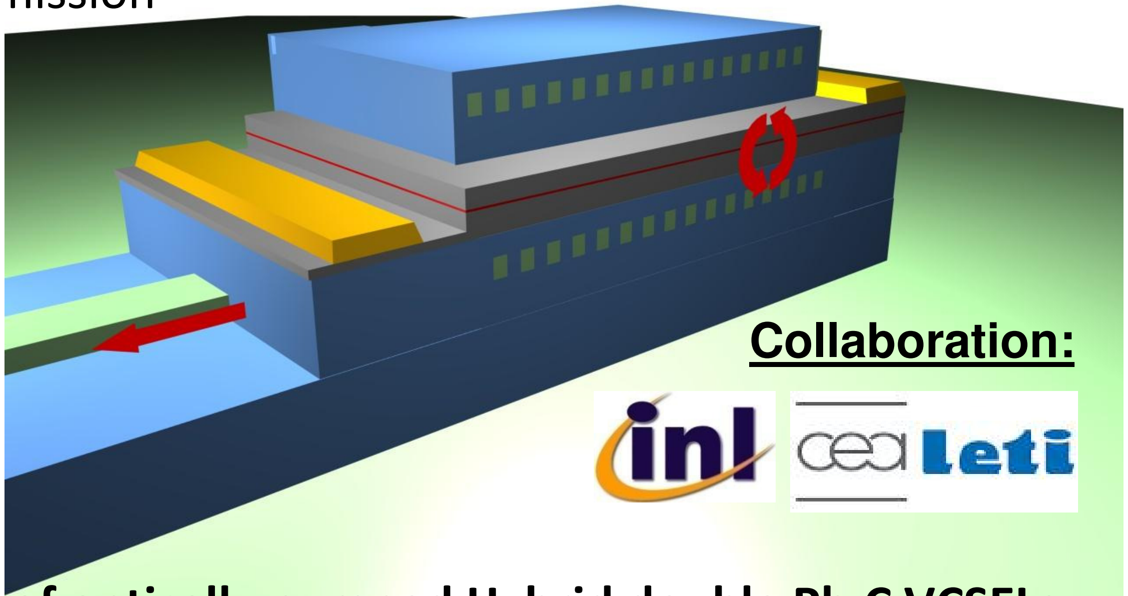






Perspectives

- Hybrid Si/III-V Double Photonic Crystals Reflectors VCSELS
  - Vertical &In-Plane Emission
  - Adiabatic couplers



  - **First demonstration of optically pumped Hybrid double Ph.C VCSELs:**

ThC6 15.00 - 15.15

CMOS-Compatible Integration of III-V VCSELs Based on Double Photonic Crystal Reflectors, C. Sciancalepore, *Institut des Nanotechnologies de Lyon, Ecully, France*, B. Ben Bakir, *Commissariat à l'Énergie Atomique, Grenoble, France*, X. Letartre, *Institut des Nanotechnologies de Lyon, Ecully, France*, N. Olivier, *Commissariat à l'Énergie Atomique, Grenoble, France*, C. Seassal, *Institut des Nanotechnologies de Lyon, Ecully, France*, D. Bordel, *Commissariat à l'Énergie Atomique, Grenoble, France*, P. Rojo-Romeo, P. Regreny *Institut des Nanotechnologies de Lyon, Ecully, France*, J.-M. Fedeli, *Commissariat à l'Énergie Atomique, Grenoble, France* and P. Viktorovitch, *Institut des Nanotechnologies de Lyon, Ecully, France*

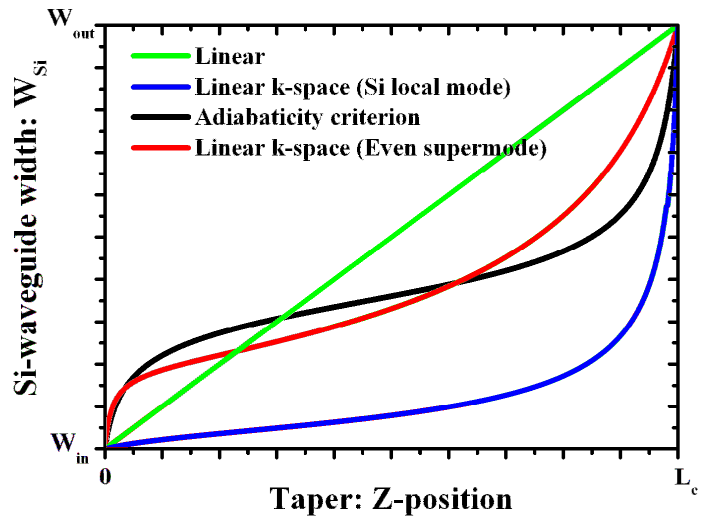
Perspectives

- Improve performances
  - Threshold, external efficiency (cavity design, current confinment)
  - Extend the operating T° range up to 80°C
- Development of new functionalities
  - Wide tunability over the C-band (30nm)
  - multi-λ transmitter module (hybrid laser+ Si-modulator+Si-multiplexer)
- Integration with other optical and electrical functions, packaging

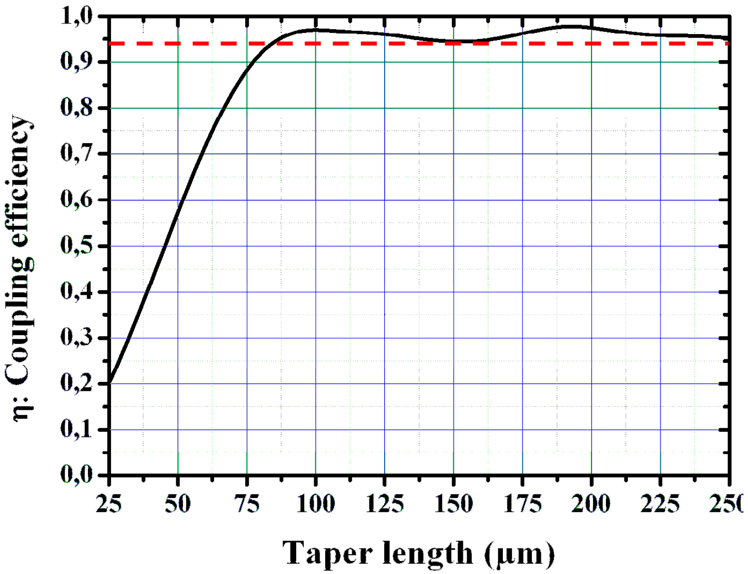
➡ Integrated transceivers on CMOS

Thank you for your attention.

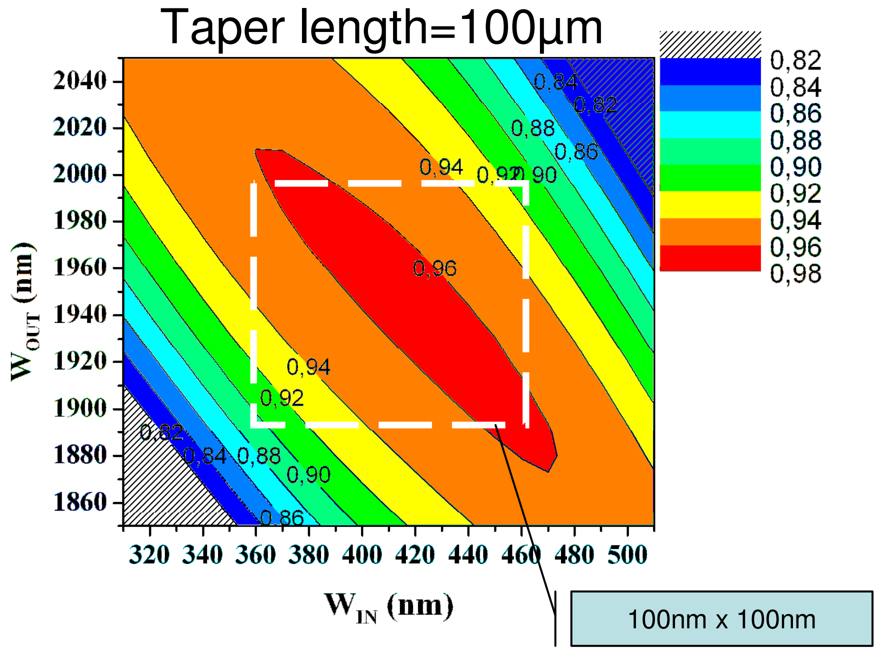
- Adiabatic



W out
W in
Si-waveguide width: W Si
Linear
Linear k-space (Si local mode)
Adiabaticity criterion
Linear k-space (Even supermode)
0
L c
Taper: Z-position

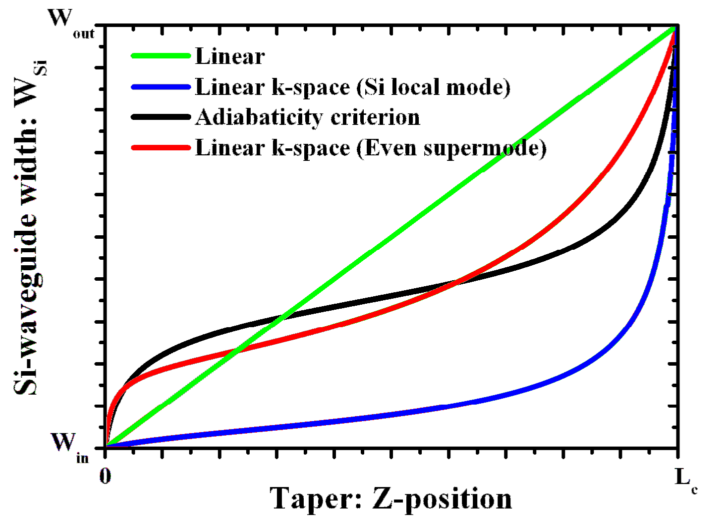


η: Coupling efficiency
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
25
50
75
100
125
150
175
200
225
250
Taper length (µm)

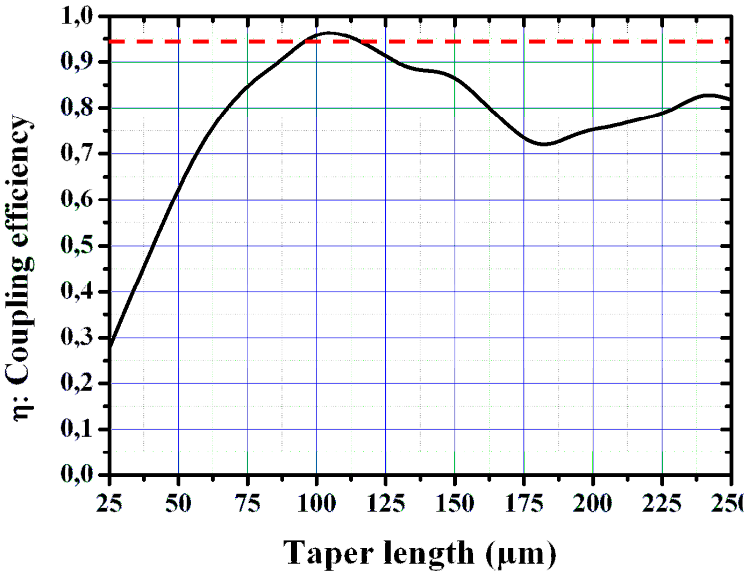


Taper length=100µm
W OUT (nm)
W IN (nm)
0,82
0,84
0,86
0,88
0,90
0,92
0,94
0,96
0,98
100nm x 100nm

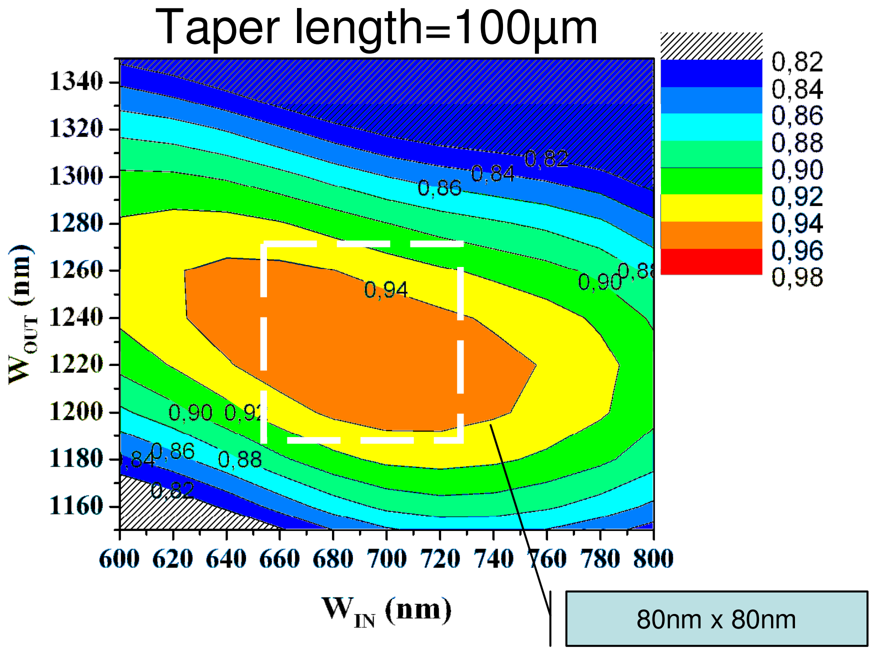
- linear



Linear
Linear k-space (Si local mode)
Adiabaticity criterion
Linear k-space (Even supermode)
Si-waveguide width: W_{Si}
W_{out}
W_{in}
0
L_c
Taper: Z-position

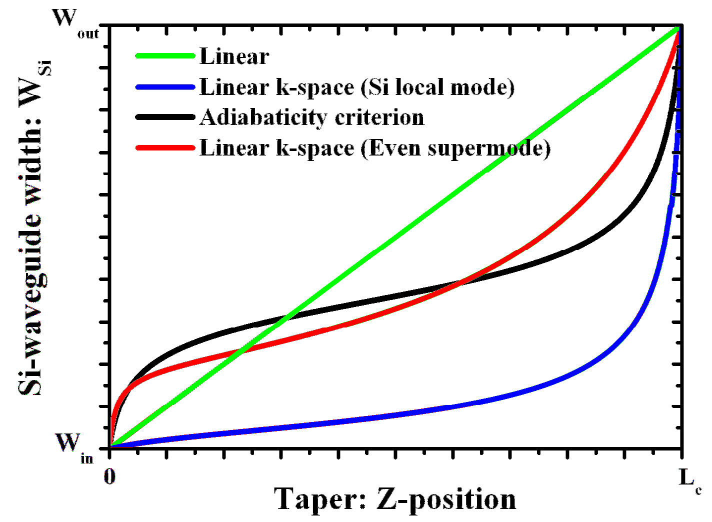


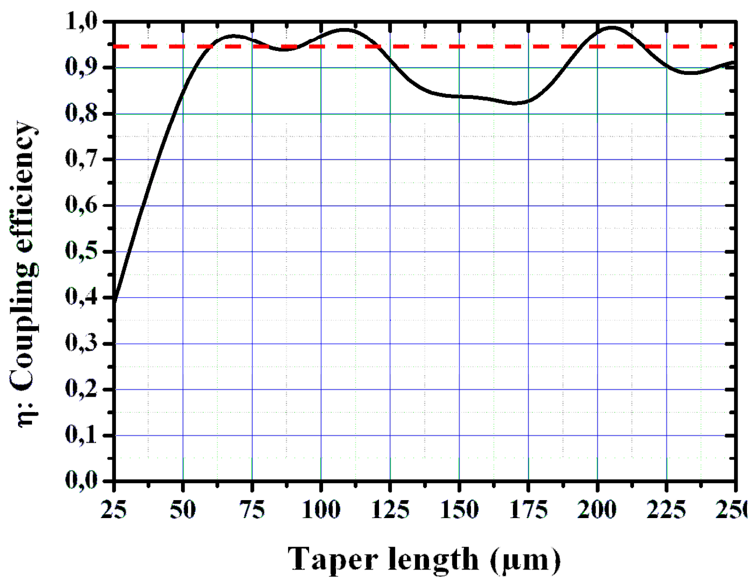
η: Coupling efficiency
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
25 50 75 100 125 150 175 200 225 250
Taper length (µm)

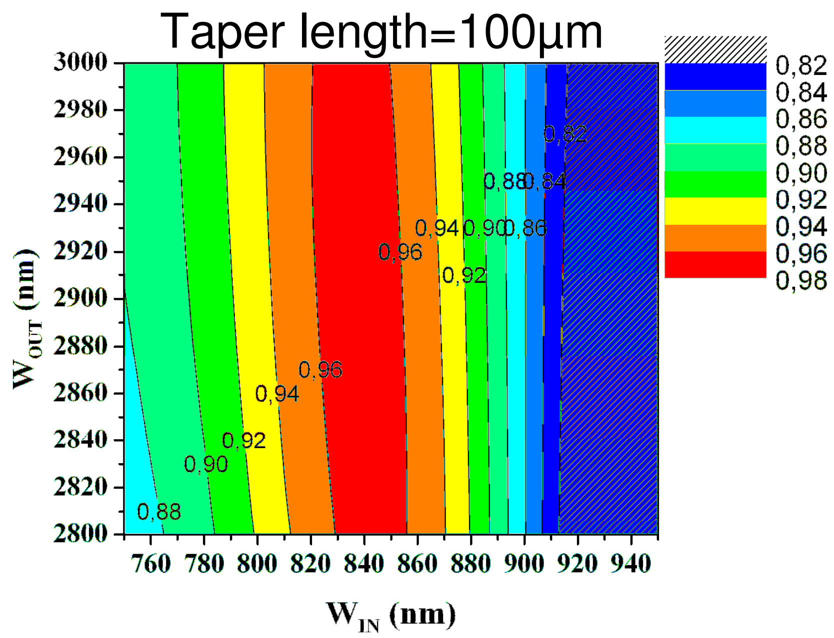


Taper length=100µm
W_{OUT} (nm)
1340 1320 1300 1280 1260 1240 1220 1200 1180 1160
600 620 640 660 680 700 720 740 760 780 800
W_{IN} (nm)
0,82 0,84 0,86 0,88 0,90 0,92 0,94 0,96 0,98
80nm x 80nm

- Linear-kspace-si

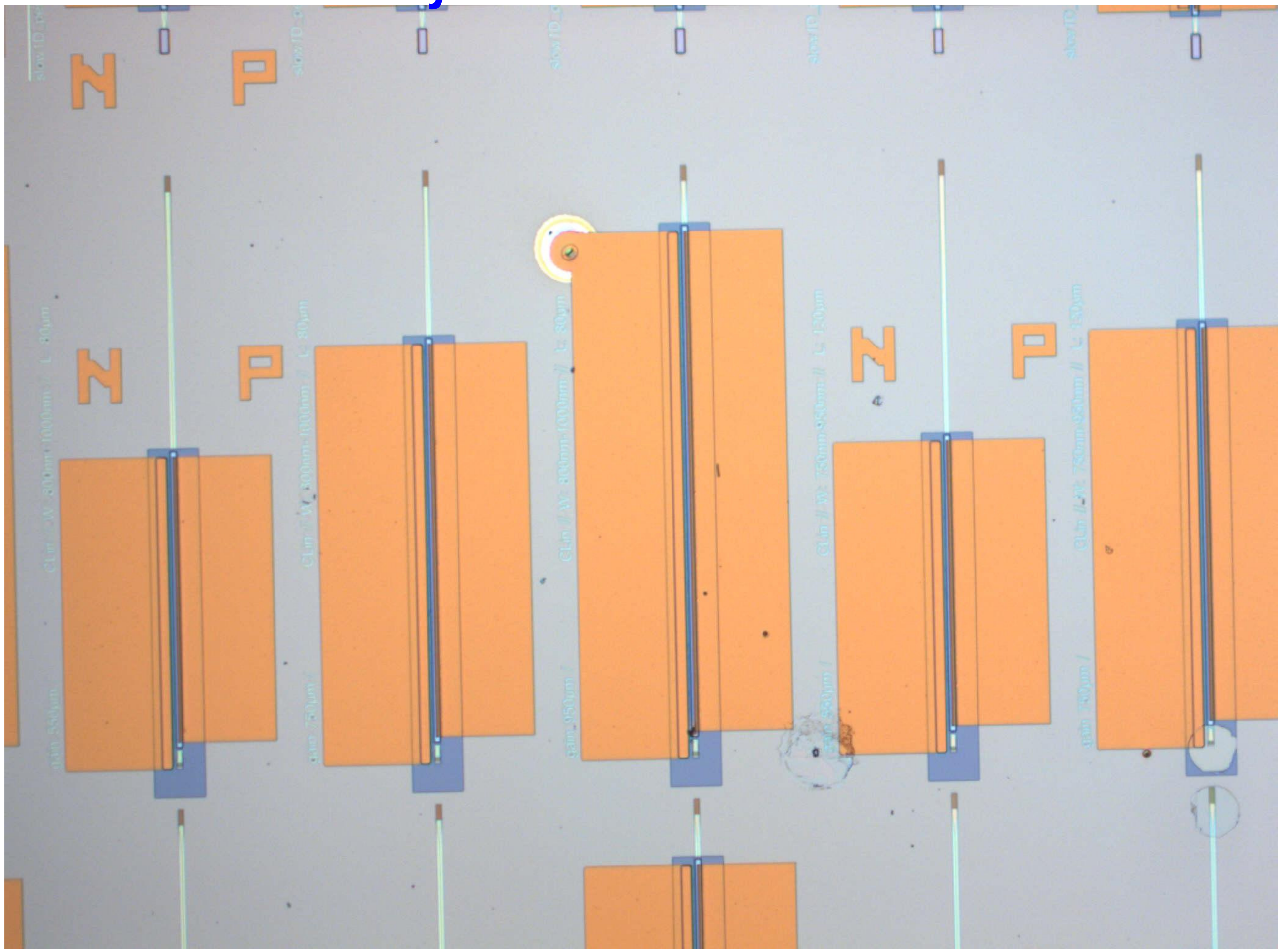






200mm- Fully CMOS compatible process

Hybrid F-P lasers



Hybrid Racetrack lasers