TELECOM PARISTECH

Photonique sur silicium : une nouvelle plateforme d'intégration photonique

Guang-Hua DUAN

12 Dec. 2012

III-V Lab, a joint lab of 'Alcatel-Lucent Bell Labs France', 'Thales Research and Technology' and 'CEA Leti', Campus Polytechnique, 1, Avenue A. Fresnel, 91767 Palaiseau cedex, France.

Outline

- **Motivation**
  - Photonic integrated circuits on silicon for optical communications
  - Comparison of InP PICs and silicon PICs
- **Current state of art of silicon photonics**
- **Hybrid III-V/Si integration technology**
  - Hybrid integration technology
  - Hybrid III-V/Si lasers
  - Integrated tunable laser- Mach-Zehnder modulator
- **Future directions**

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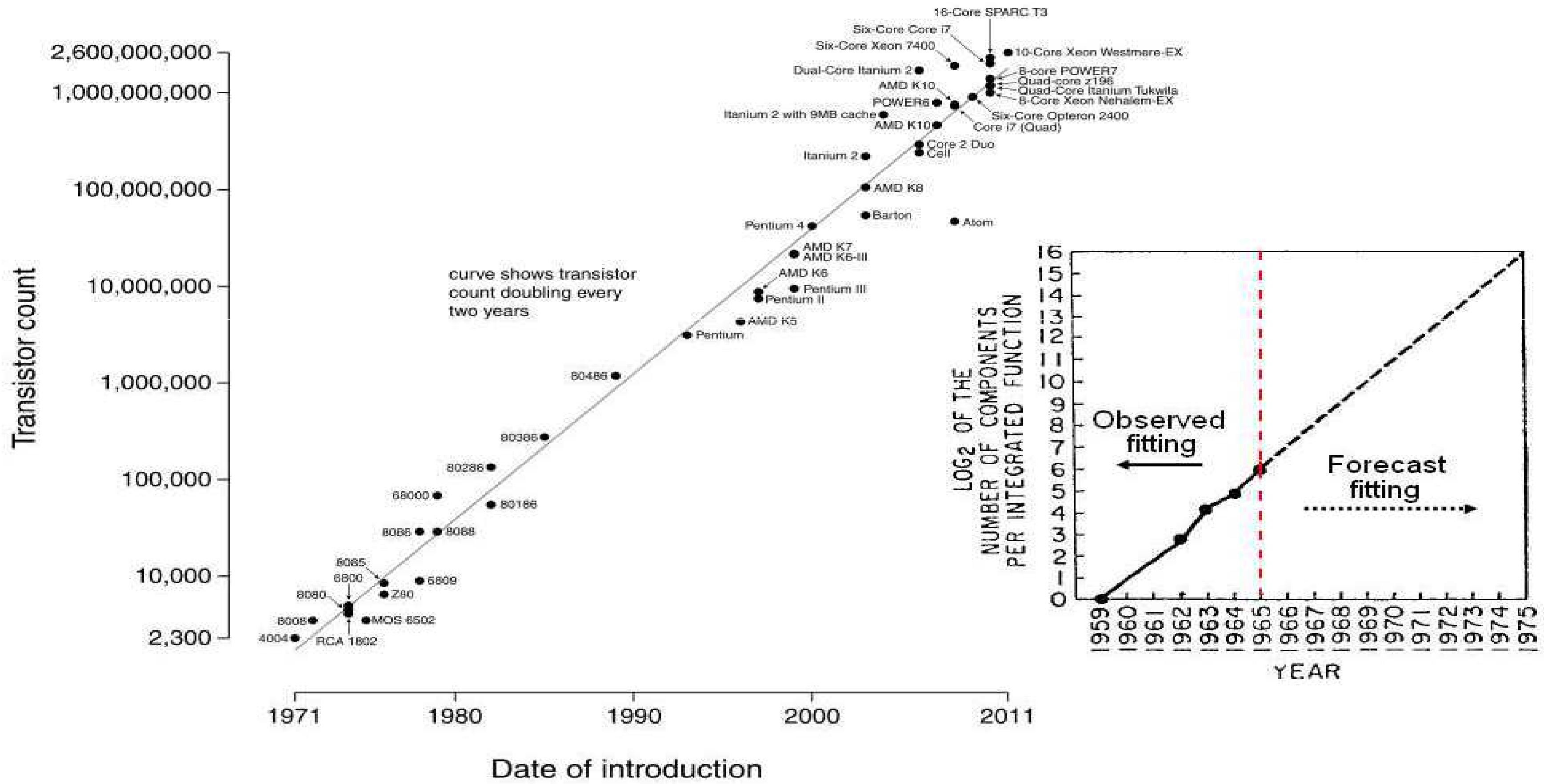
Electronic integration: Moore’s law

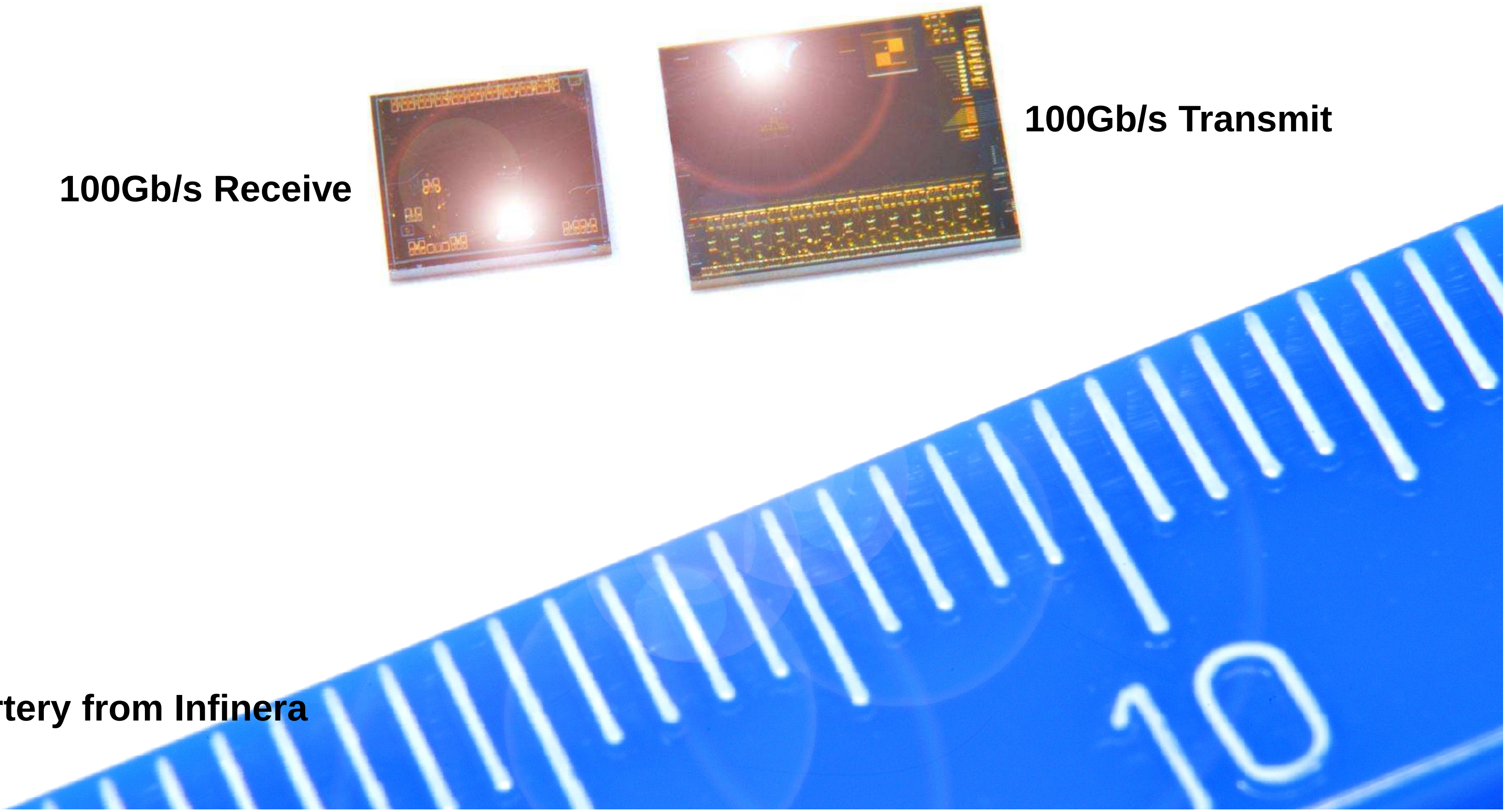
Microprocessor Transistor Counts 1971-2011 & Moore’s Law



Photonic Integrated Circuits

100Gb/s Receive

100Gb/s Transmit



Courtery from Infinera

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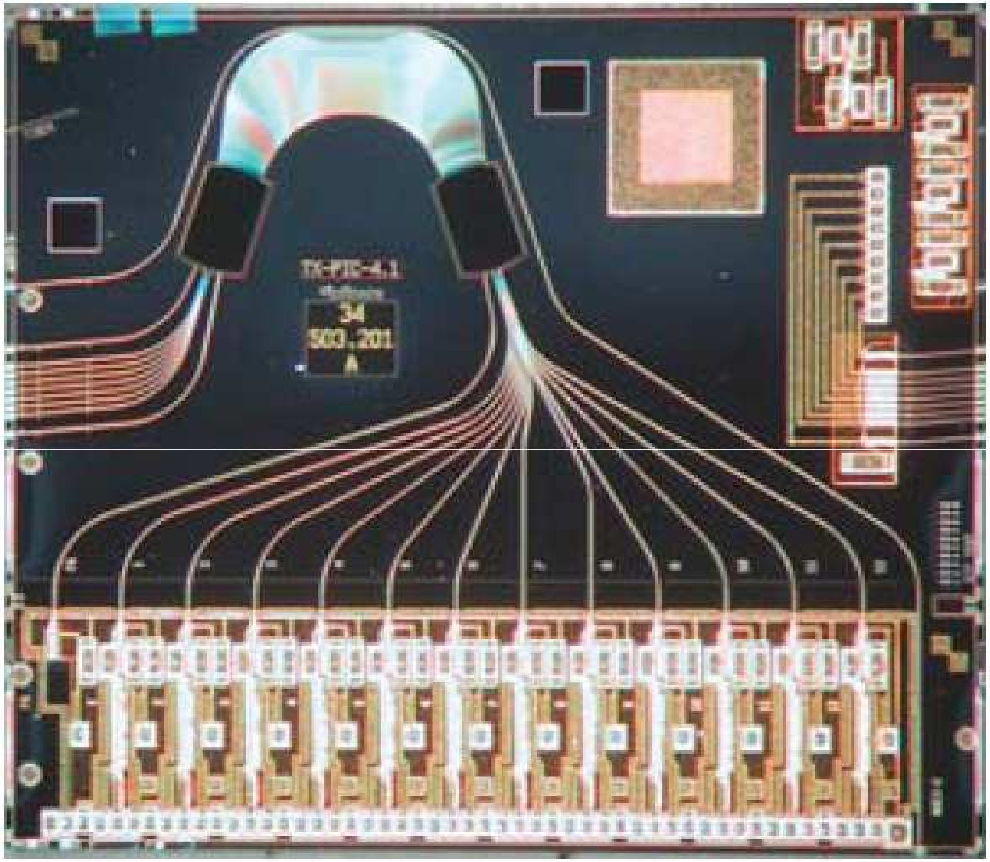
PIC: an on-going (r)evolution



Photonic Integration

Small footprint
Cost effective
Reduced power consumption

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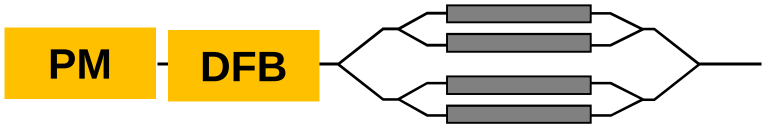
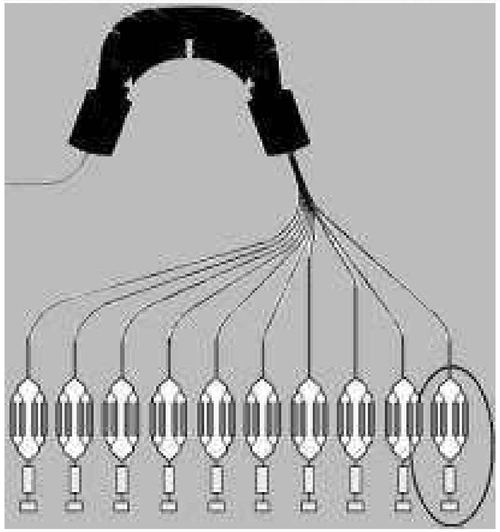
PIC for QPSK transmitter

Infinera's QPSK transmitter:

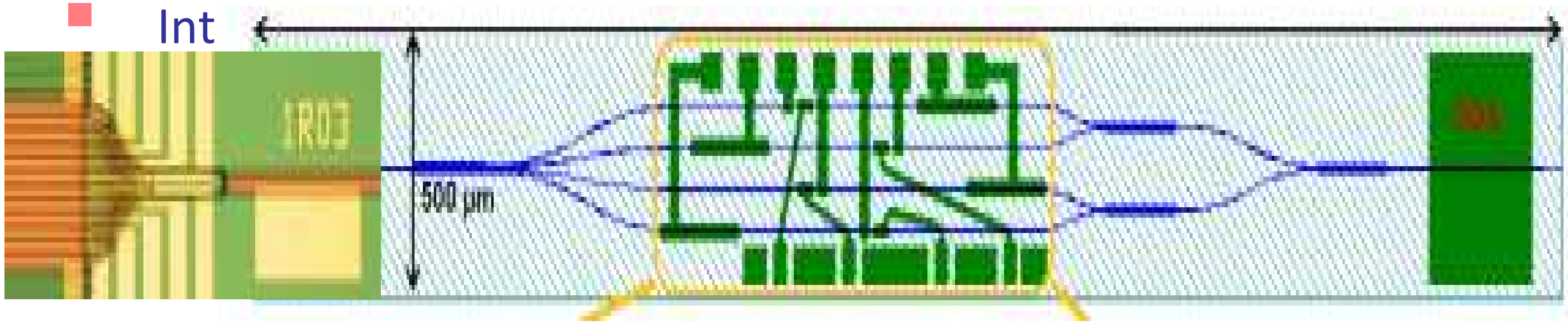


Nested MZM



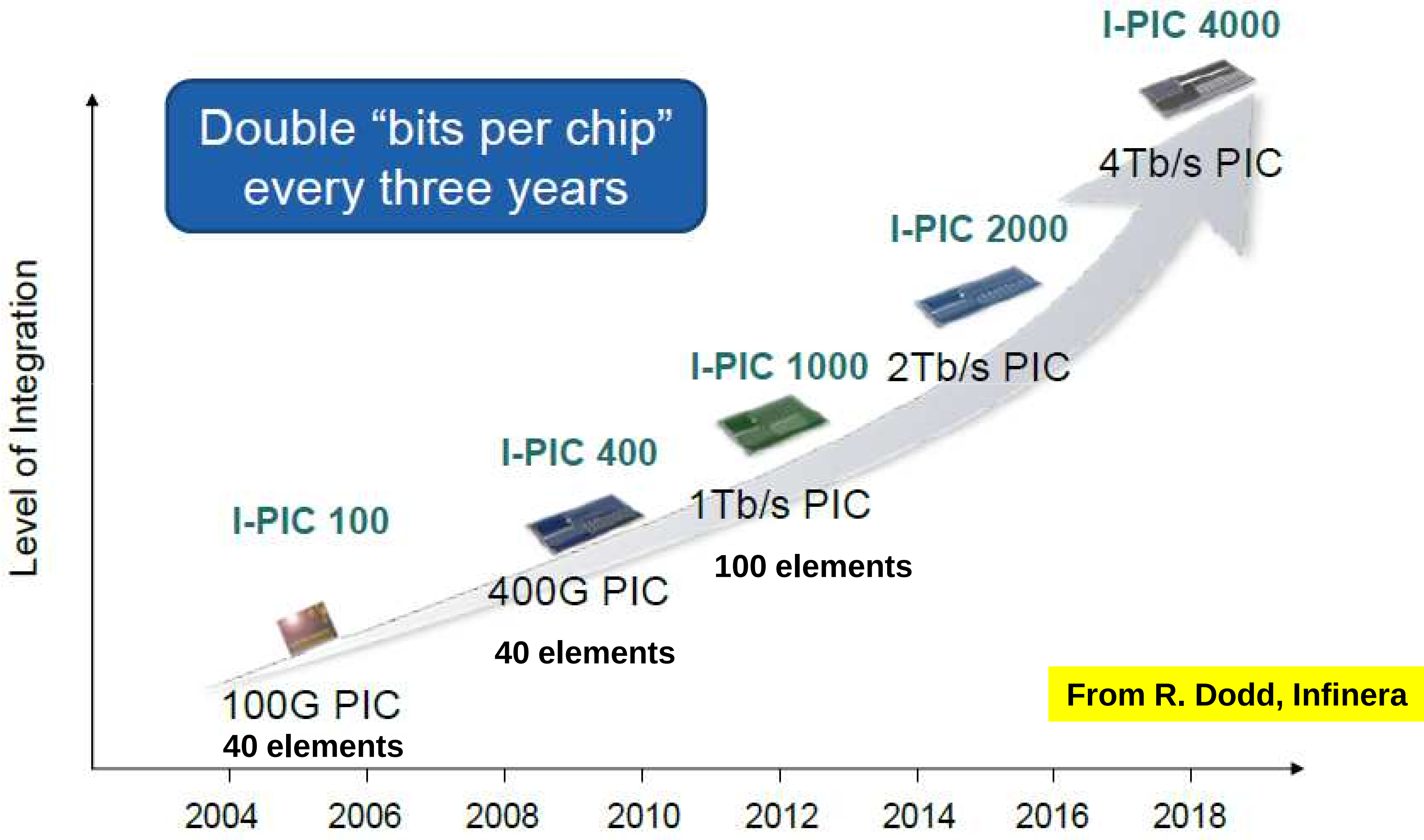
Bell Lab's QPSK/QAM Source

- Int



I. Kang, Optics Express 2007

Roadmap of Infinera's PICs



Photonic integrated circuits on silicon

CMOS EIC platform on silicon

- Mature industrial process with high yield
- Foundry model for cost-effective industrial production
- Cost-effective for large volume

PICs on silicon

- Taking benefit for EICs: industrial tools, foundry models, etc.
- Co-integration with CMOS electronics, close proximity between signal processing unit and photonic elements
- Providing optical interconnect solutions for “More than Moore” for EICs

Can silicon be a Photonic integration plateform?

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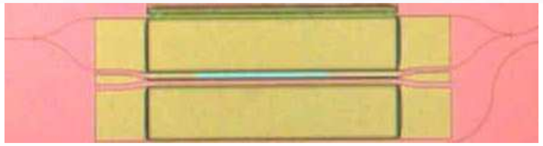
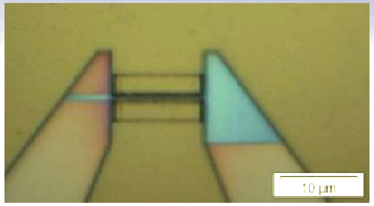
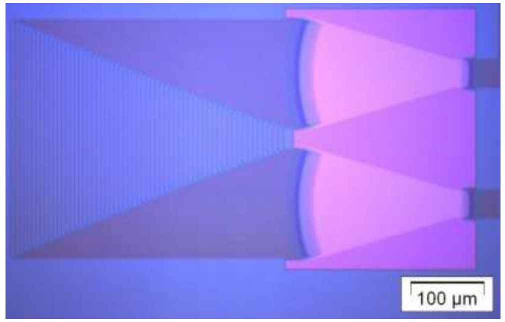
The building blocks



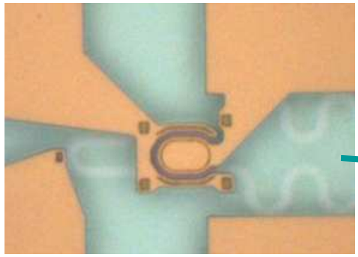
Optical modulator



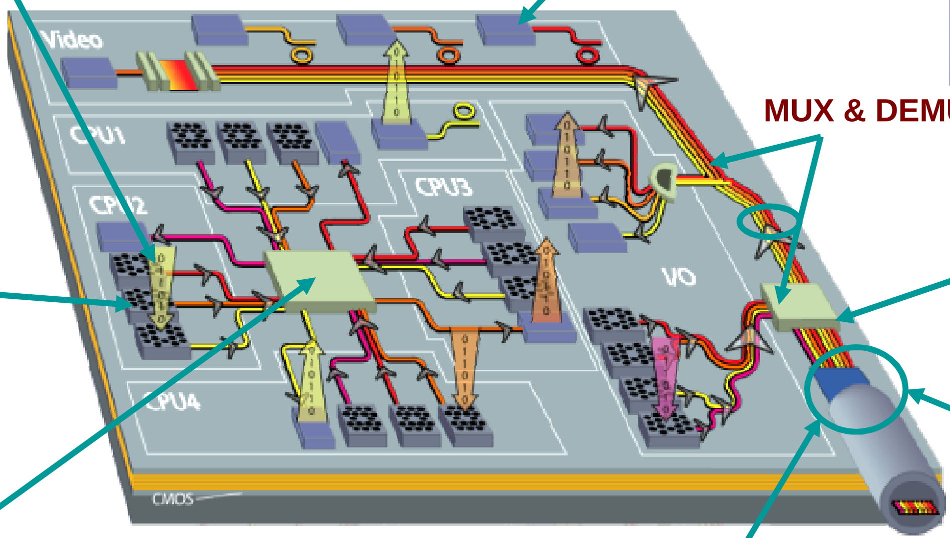
Photodetector



MUX & DEMUX



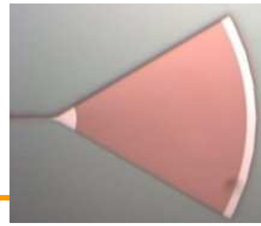
Laser source



Waveguide

Grating coupler

In-plane coupler



Optical switch

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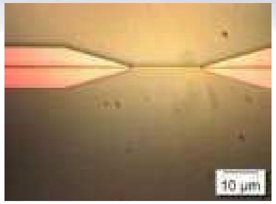
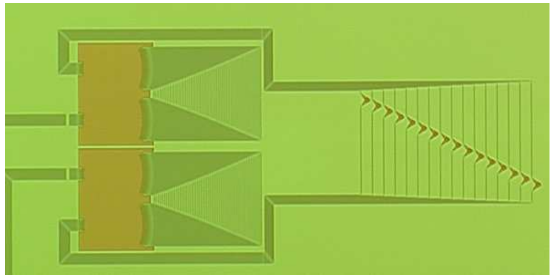
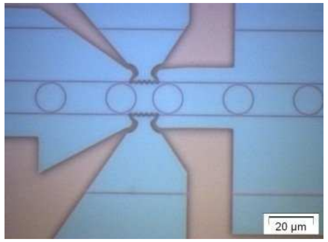
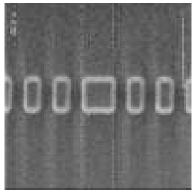
I/O & waveguides

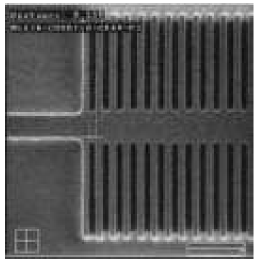
Waveguides
- **Transitions**
- **Splitters**
- **MMI**
- **Resonators**
- **AWG**
- **oNoC**
- **Slow wave structure**

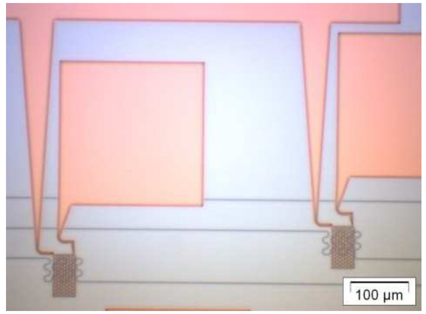




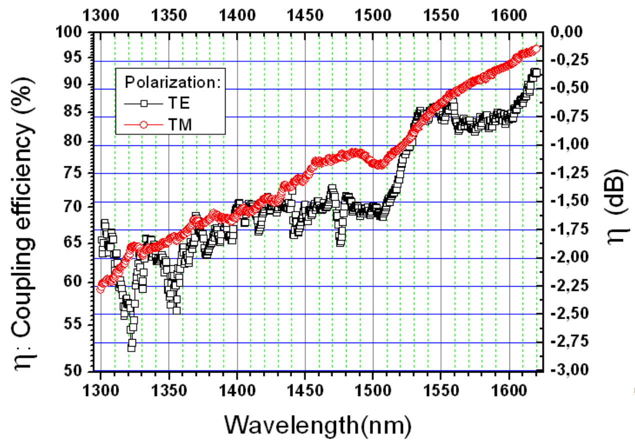




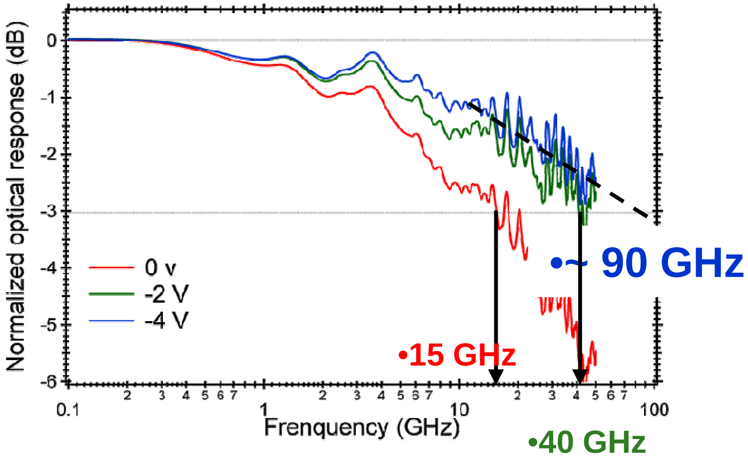


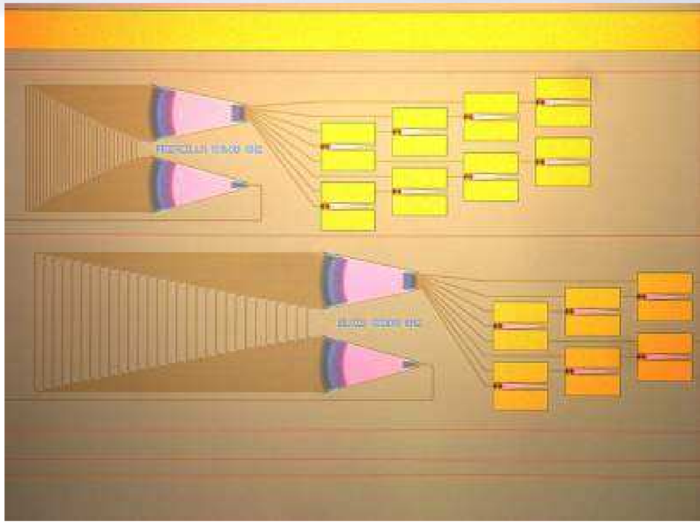


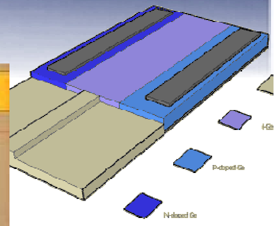
Edge coupling with inverted taper: <1dB losses

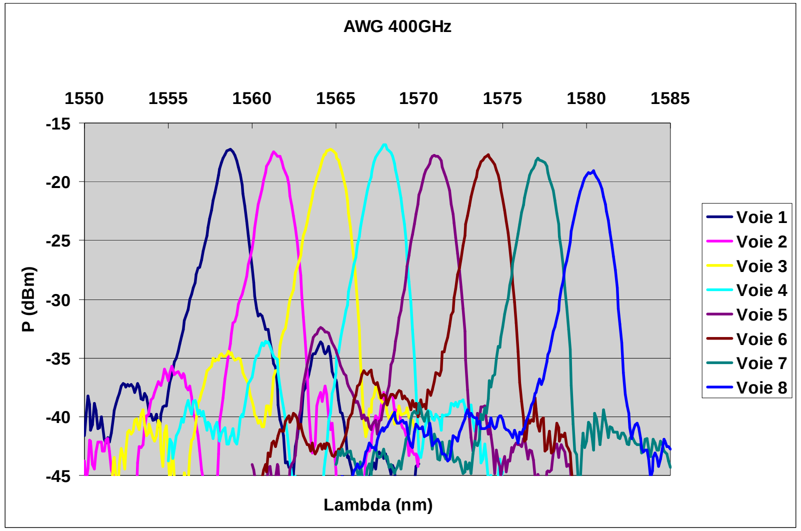


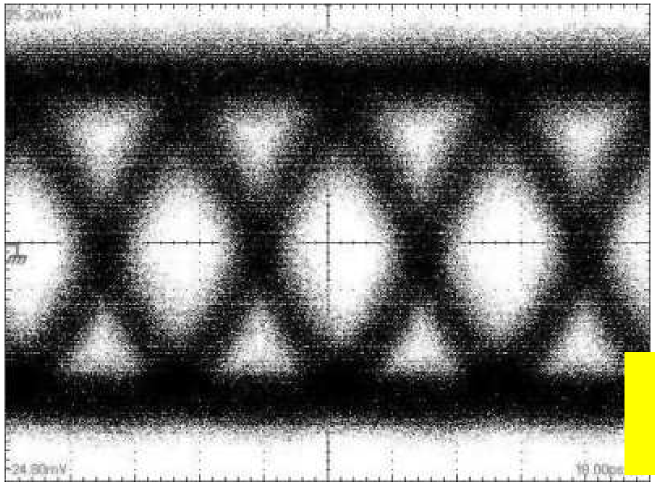
•Germanium photodetectors











From L. Vivian, IEF

•Eye diagram @ 40Gbps

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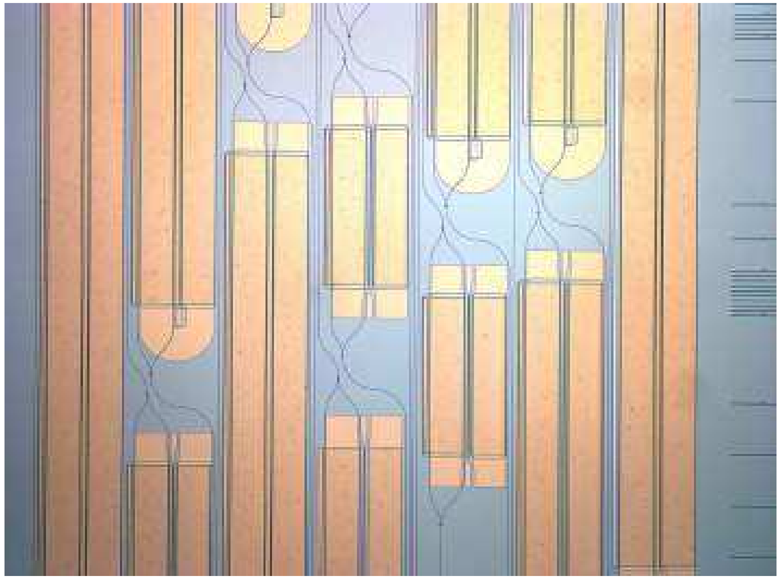
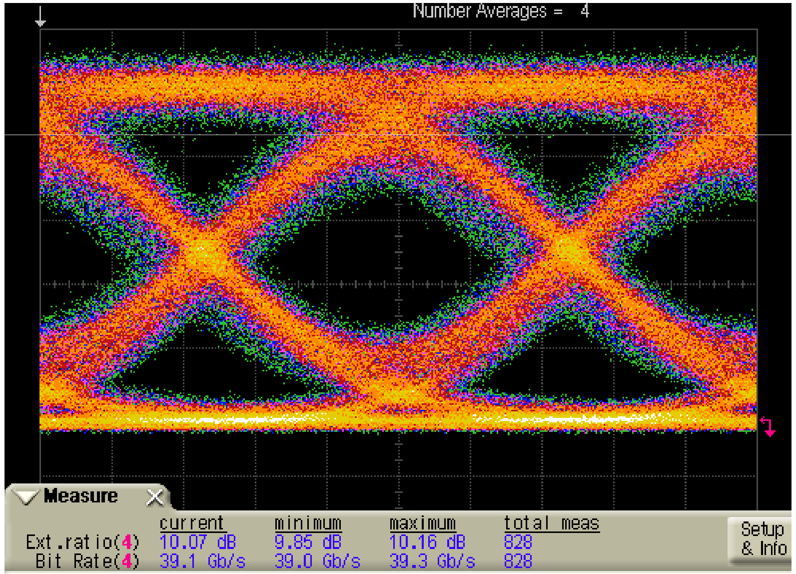
Carrier depletion modulators

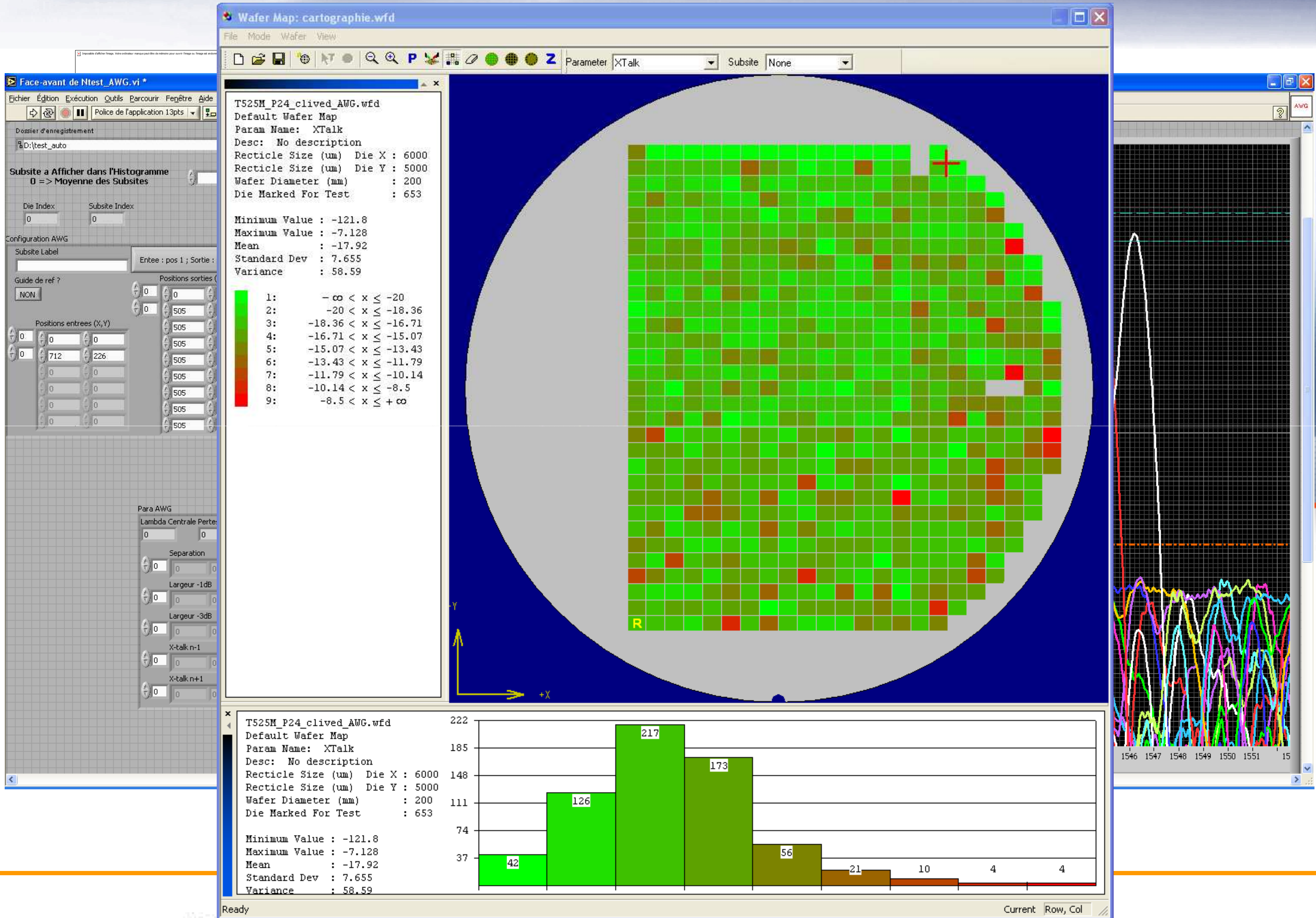
- 40Gb/s demonstrated with 10dB extinction ratio
- Tradeoff between losses, power consumption and extinction ratio





From D. Morris, IEF

Wafer level testing



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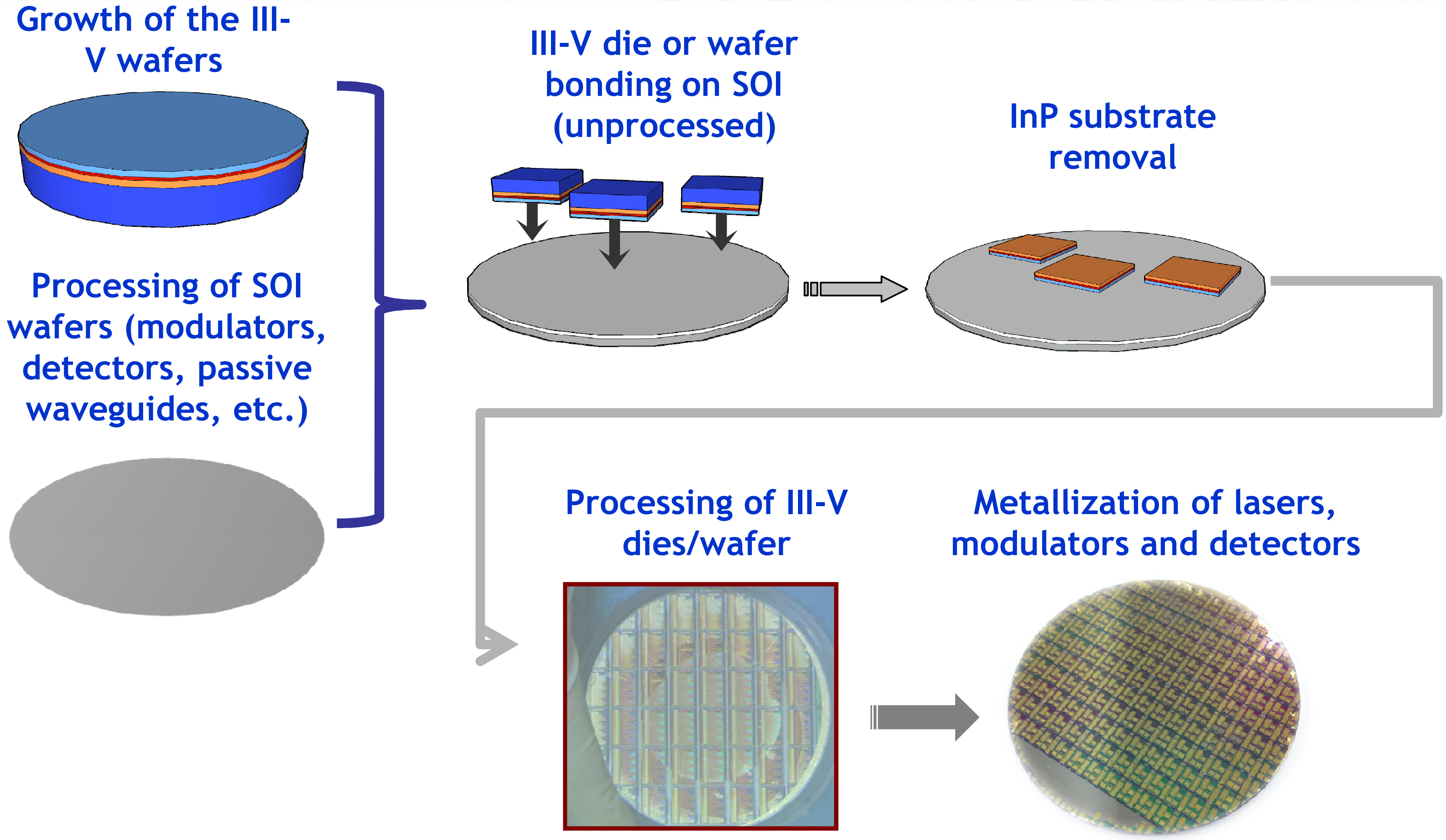
Photonic Integration : InP vs Si Photonics Platforms

	InP platform (III-V Lab)	Si-photonics platform (III-V Lab, CEA, LETI)
Functionality	Source, Detector, Waveguide, Modulator	Detector, Waveguide, Modulator **Massive electronic integration** **No source: need for InP hetero-integration or Ge sources**
Performance	**Excellent optical performance** **No large scale integration with electronics**	Good optical performance **Large scale integration with electronics for 'free'**
Footprint	Large for passive elements (AWG, ring resonators, etc)	**Compact for passive elements (AWG, ring resonators, etc)**
Cost	Higher due to individual device testing, Low yield for PICs	**Wafer scale testing** **CMOS processing & monitoring for 'free'** **Foundry model for volume production will drive cost down**
Power consumption	Low for electro-absorption modulator, higher for Mach-Zehnder type modulator	Novel modulator design results in low drive voltage

Our Vision on Silicon PICs

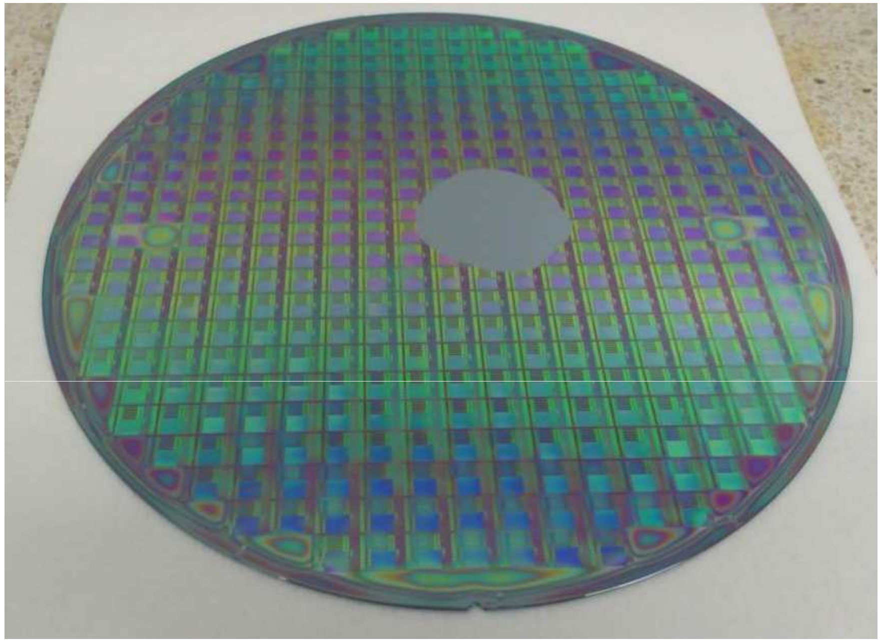
- **Silicon photonics approach:**
  - Mature CMOS fabrication process
  - Available key building blocks: modulators, detectors, low loss passive waveguides, wavelength multiplexers/demultiplexers
  - Lack of efficient lasers sources on silicon
- **Sources for silicon photonics**
  - Ge on silicon lasers and Epitaxy of III-V layers on silicon through a buffer layers: very promising results, but still requiring developments
  - Hybrid III-V/Si integration using wafer bodning: most efficient solution today
- **Hybrid III-V/Si integration combing advantages of III-V and Si**
  - III-V: providing optical gain
  - Si: providing wavelength selection and tuning using passive silicon waveguides
  - Dies to wafer or wafer to wafer bonding proven to be a reliable process for SOI wafers
  - => a new classe of tunable lasers with large tuning range, high SMSR and compact size
  - = > PIC transmitter integrating tunable lasers and silicon modulators

Heterogeneous integration

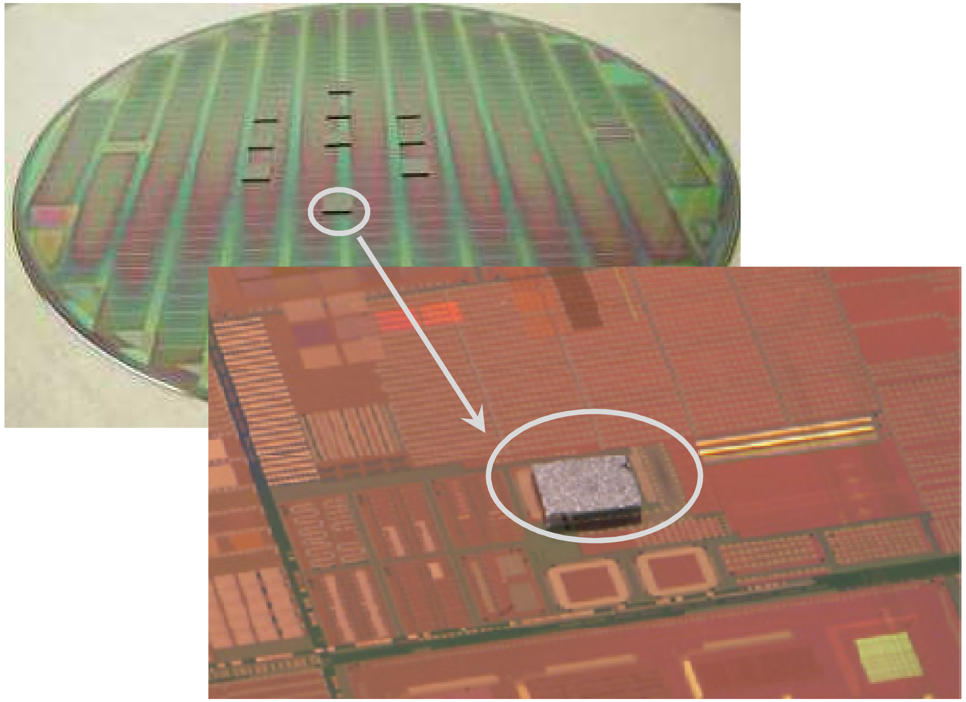


Bonded III-V wafers/dies on SOI

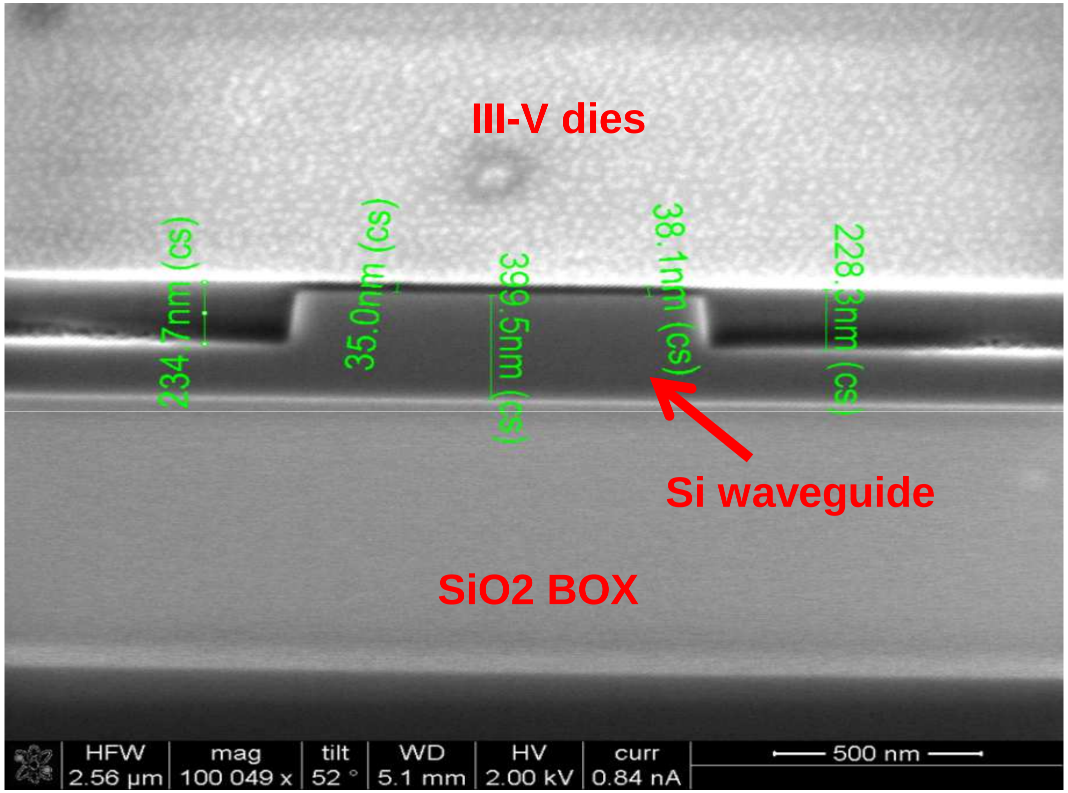
Wafer to wafer bonding



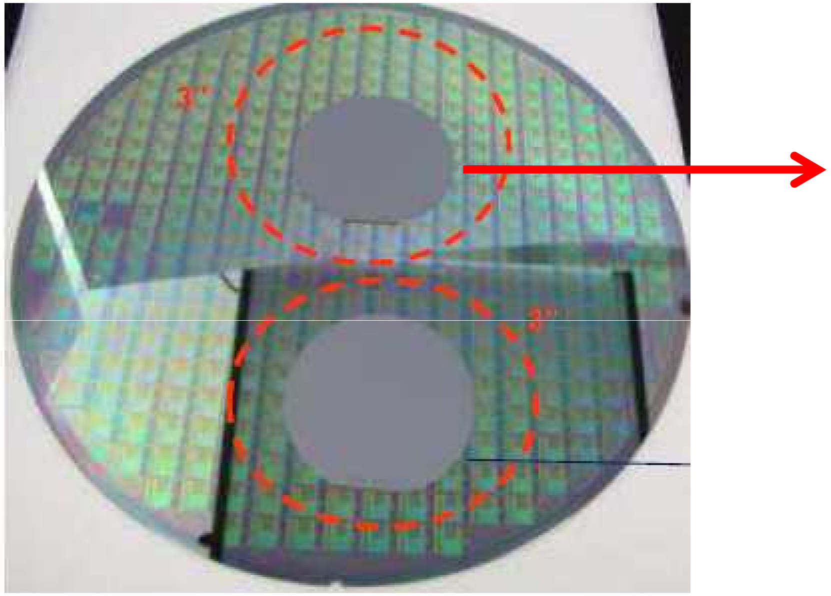
Dies to wafer bonding

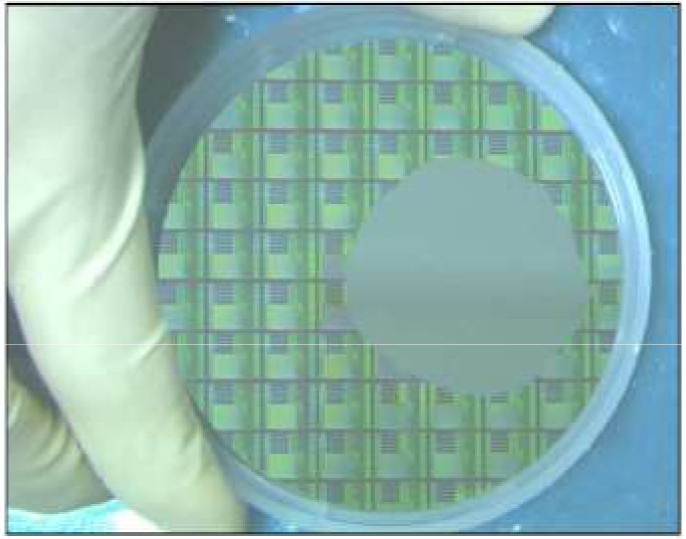


Bonding of III-V dies on SOI wafer



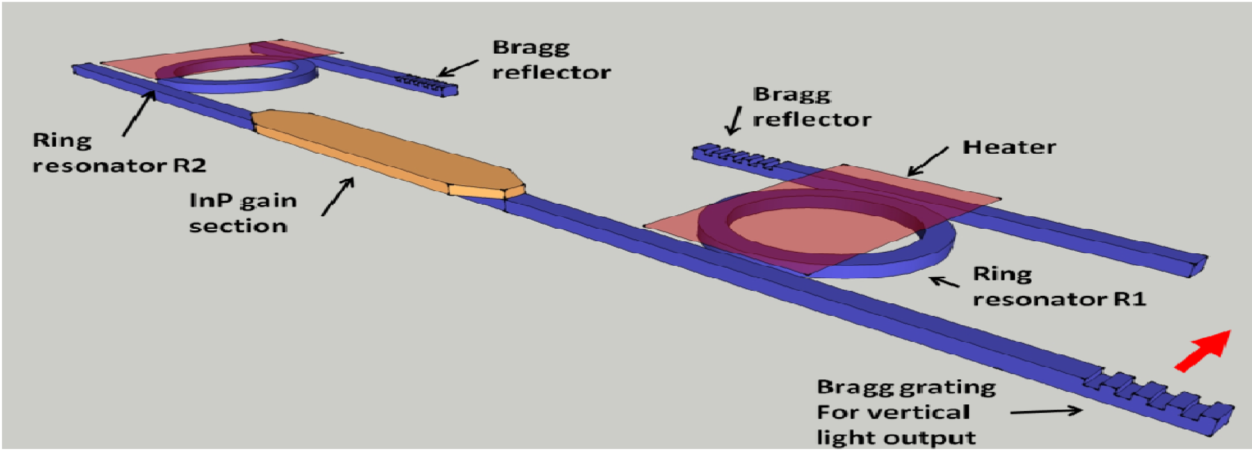
Processing of III-V lasers on silicon

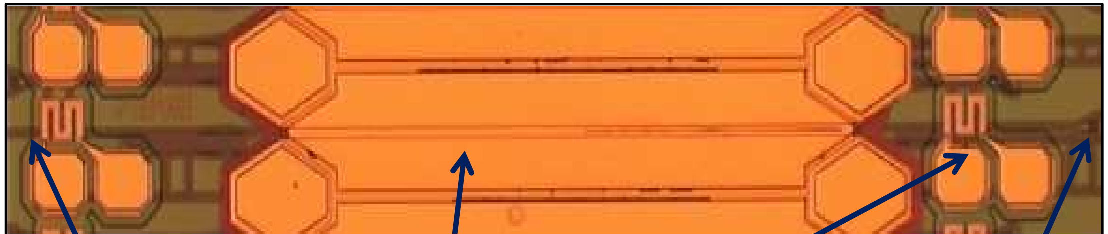




Laser cutting of 8" wafers into 3" wafers, ready to be processed in a III-V foundry

Tunable lasers with 45 nm tuning range

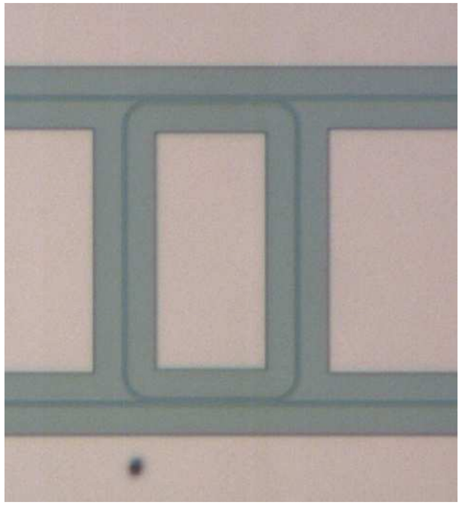




A. Le Liepvre, et al., GFP Conference, Aug. 2012

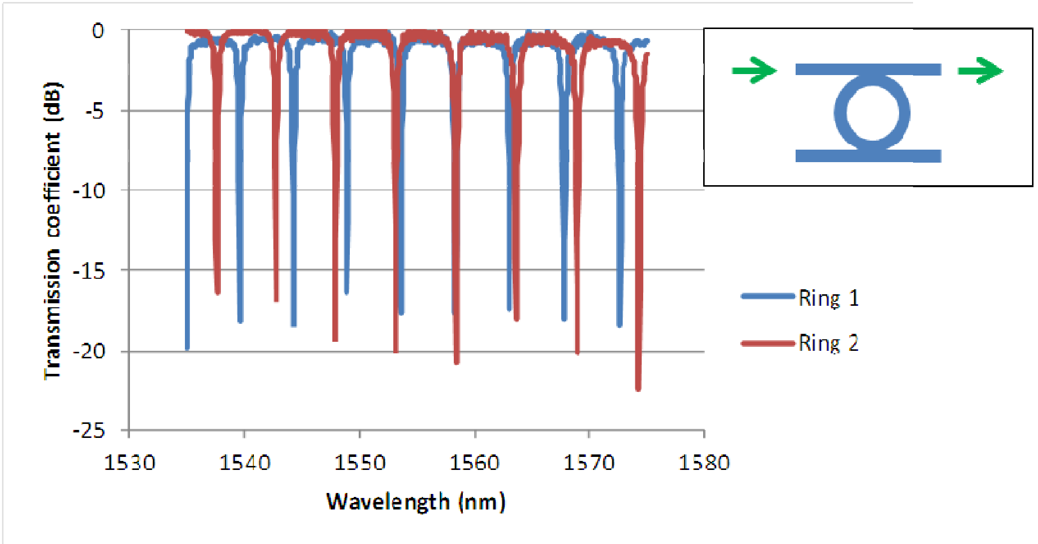
Silicon Racetrack ring resonator

- **Low loss in waveguides and bends**
  - 90° Turn : 0.01 dB loss for 5µm radius
- **High finesse (> 10) ring/racetracks resonators in Si with FSR around 5nm**



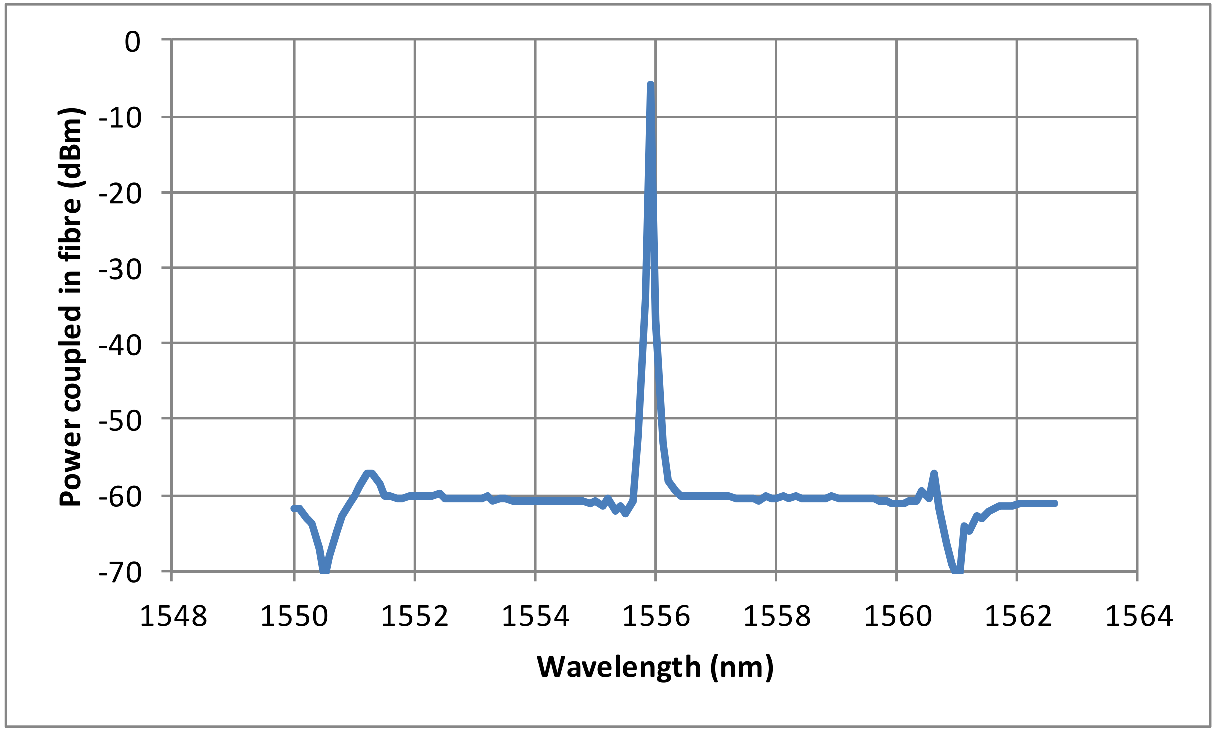
Si Racetrack resonator

Measured transmission of two ring resonators used in the laser



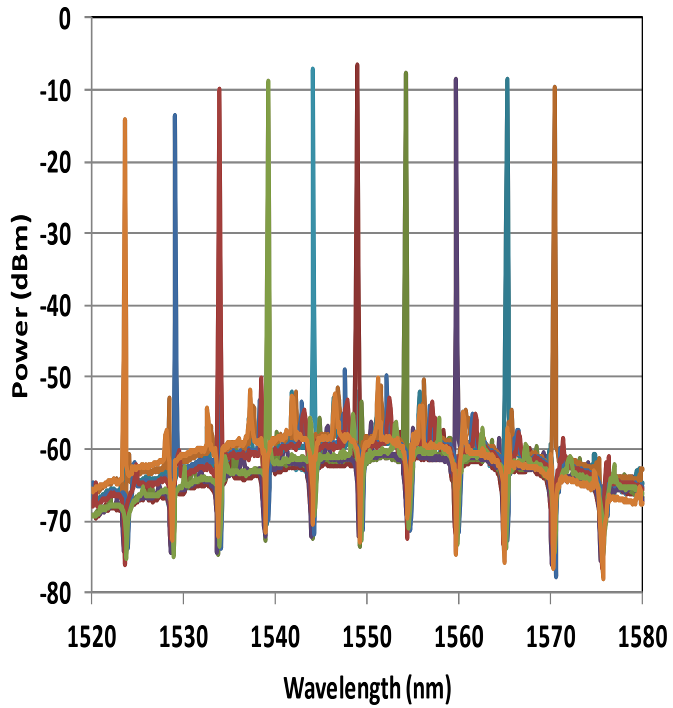
Main Laser CW Characteristics

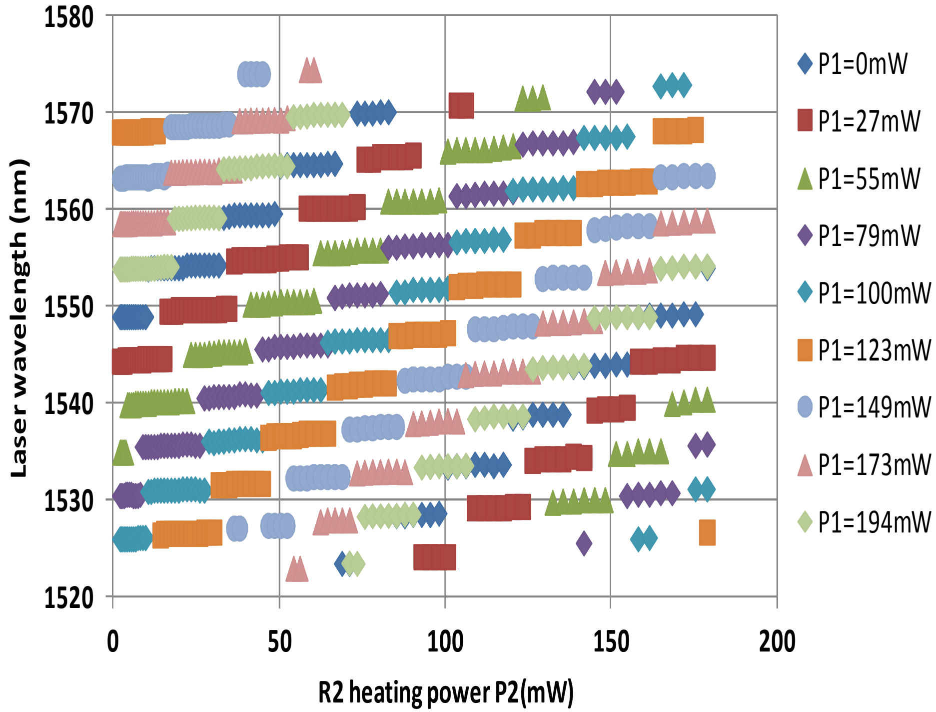
- Threshold : 22mA, maximum total output power 10 dBm
- Single-mode operation with SMSR > 40 dB
- Series resistance : 5-6 Ω



Laser spectrum for I=80mA, T=20℃

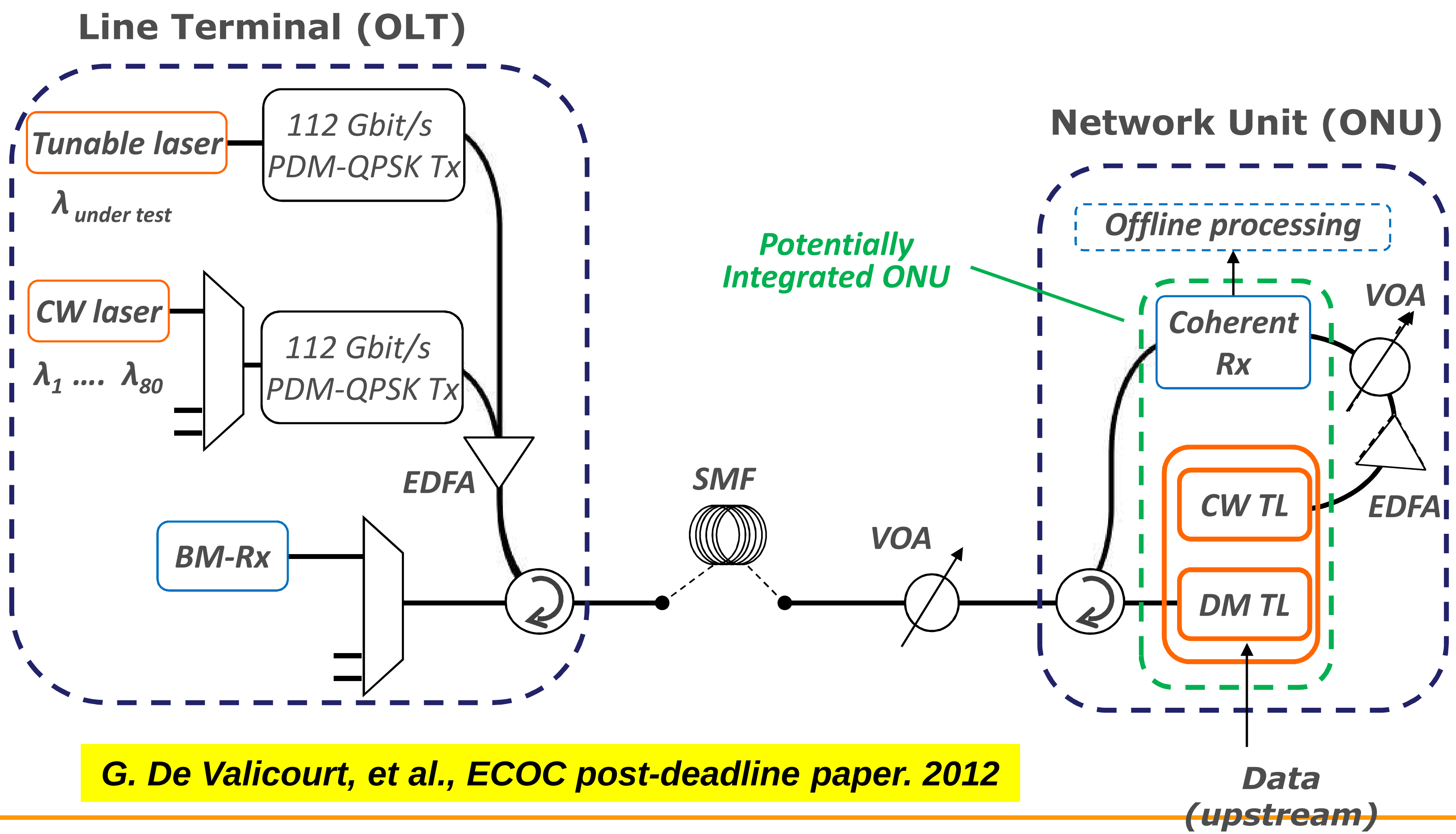
Wavelength tuning curves





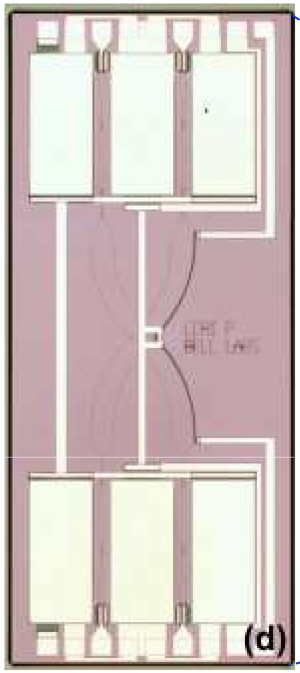
- **45 nm tuning range with SMSR > 40 dB over the tuning range**
- **More robust single mode operation than InP based tunable lasers**

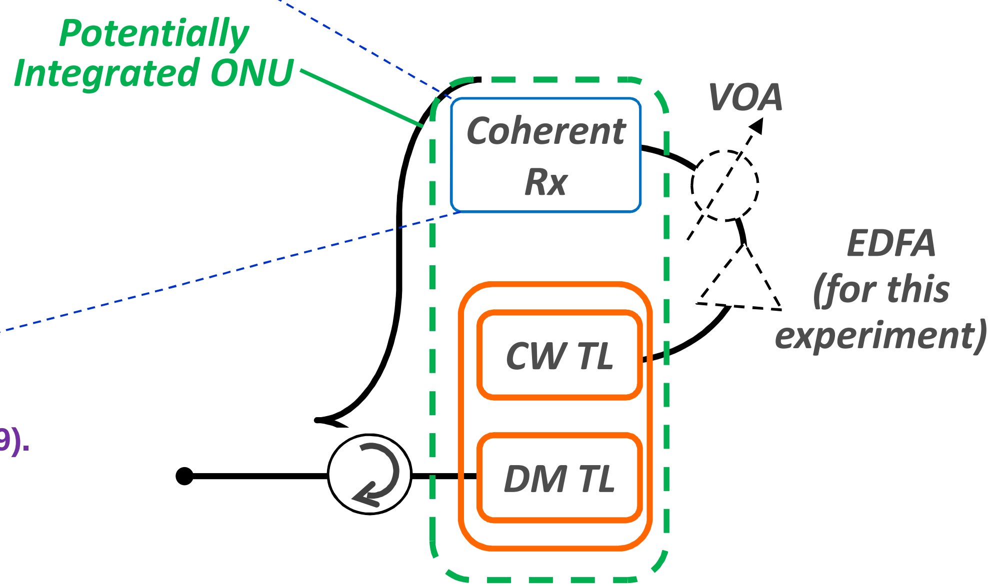
Tunable transmitter and local oscillator in a coherent receiver



G. De Valicourt, et al., ECOC post-deadline paper. 2012

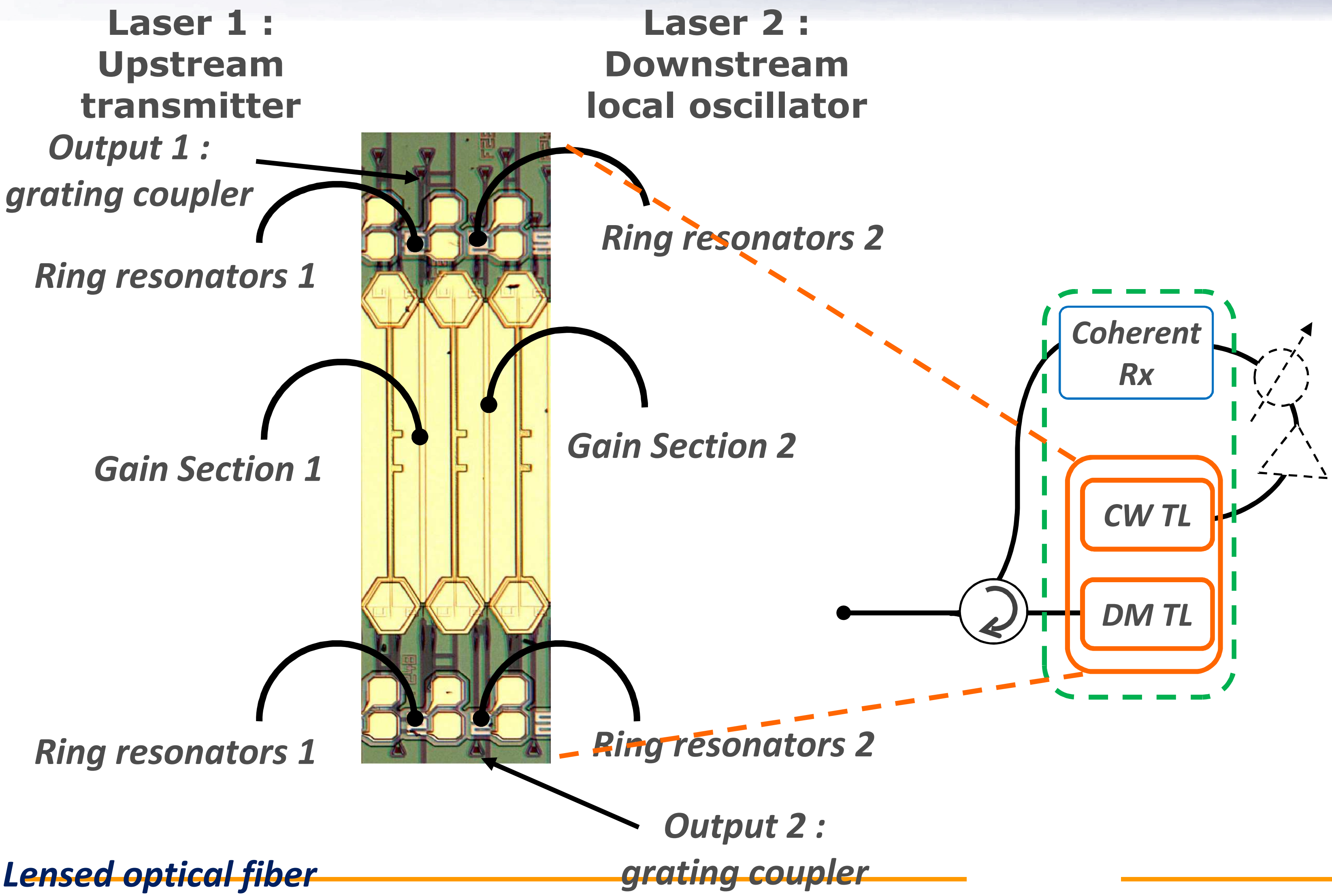
Coherent colorless Optical network unit





[1] C. R. Doerr et al., Proc. OFC'09, PDPB2 (2009).

Hybrid III-V/silicon lasers



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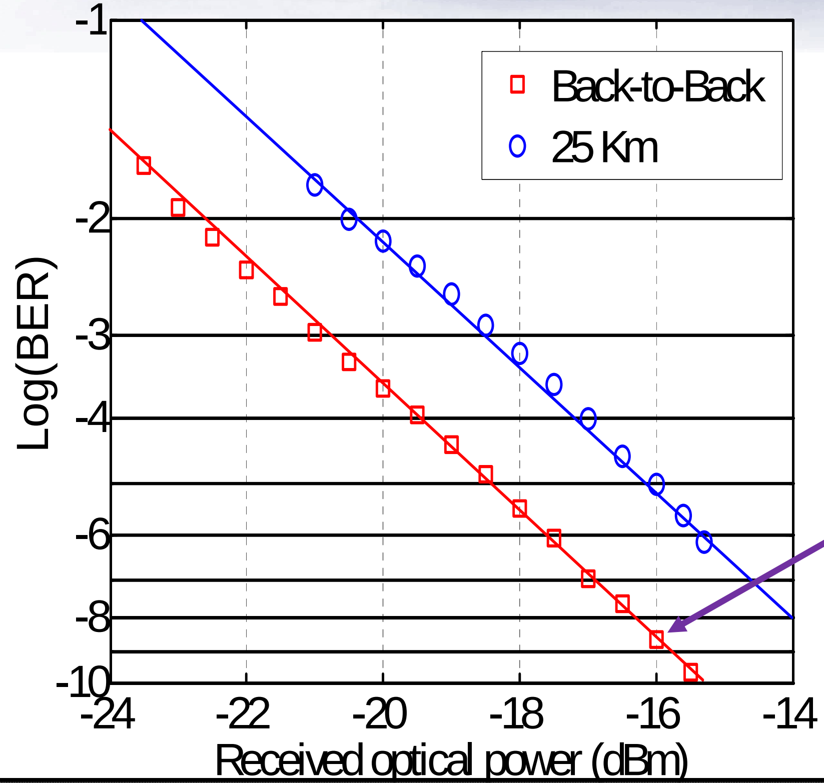
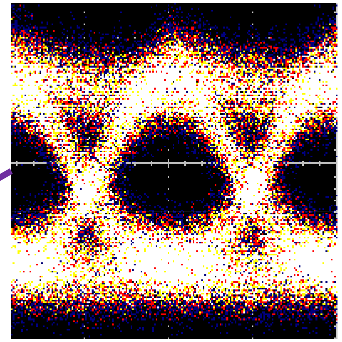
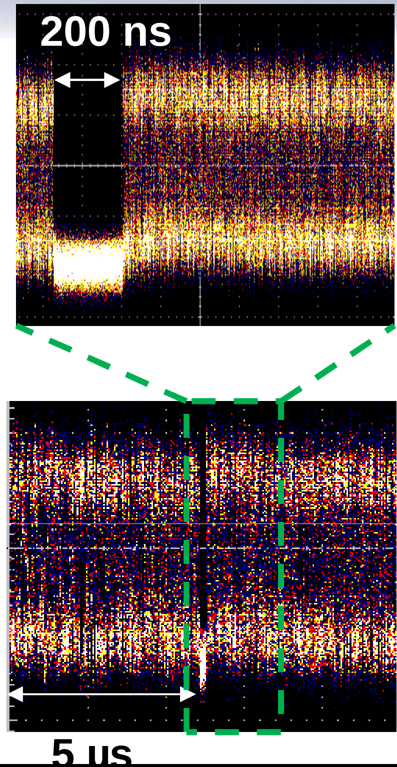
Directly modulated tunable hybrid laser





10 Gbit/s OOK burst mode operation



❖ Less than 2.5 dB of sensibility penalty after 25 km

Dynamic reconfiguration of client connections with joint flexibility in time and wavelength domains

❖ Could be reduced by using more advanced coupling structure and new laser design (actual coupling loss:~8dB)

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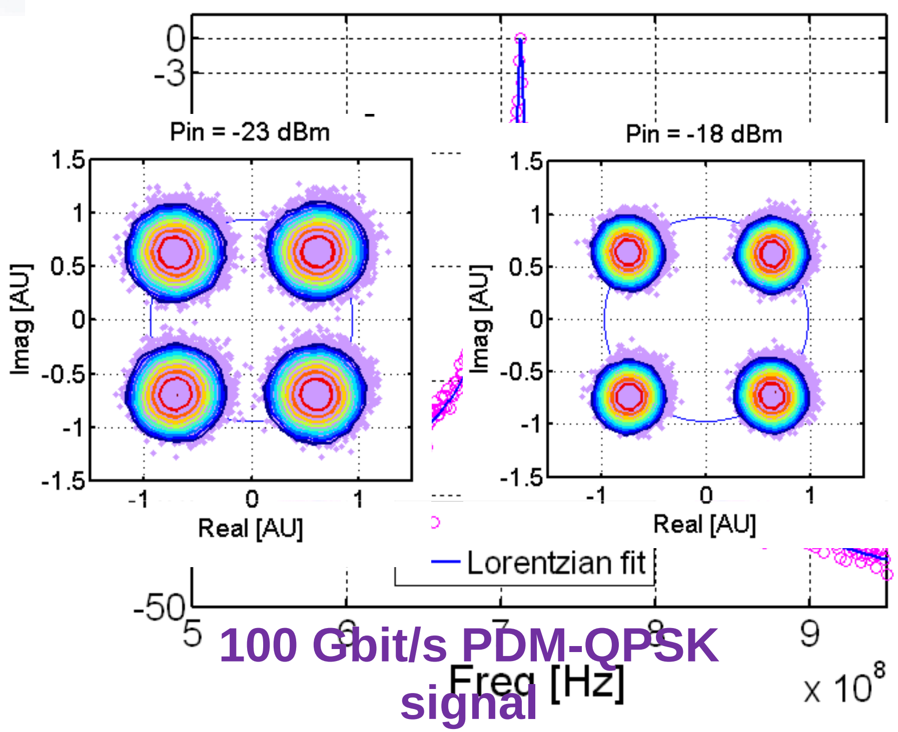
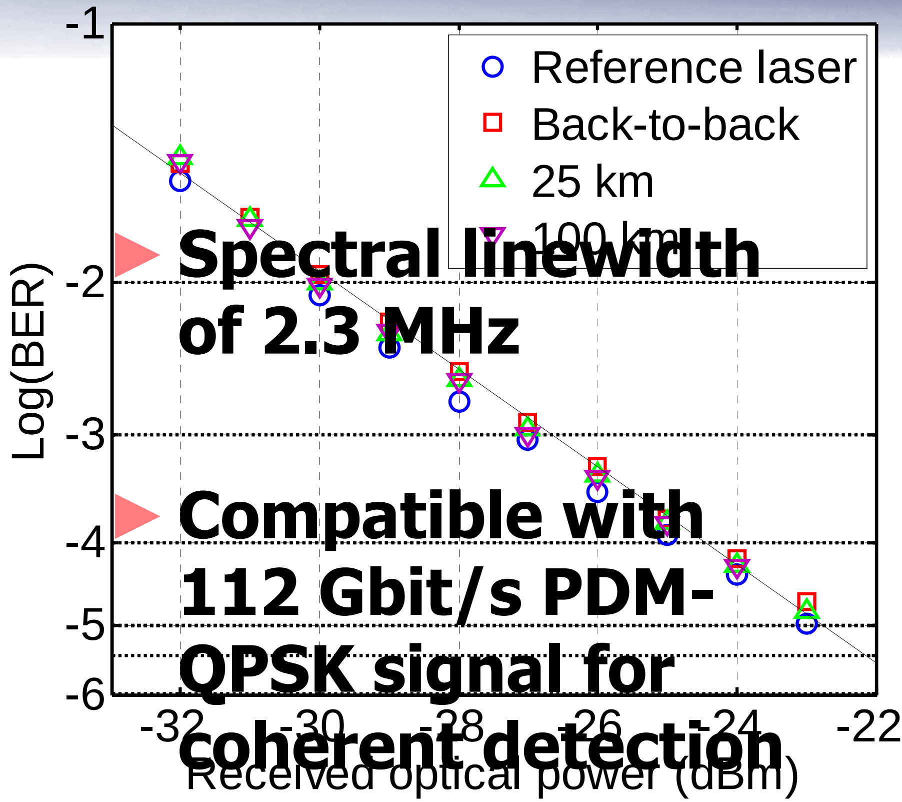
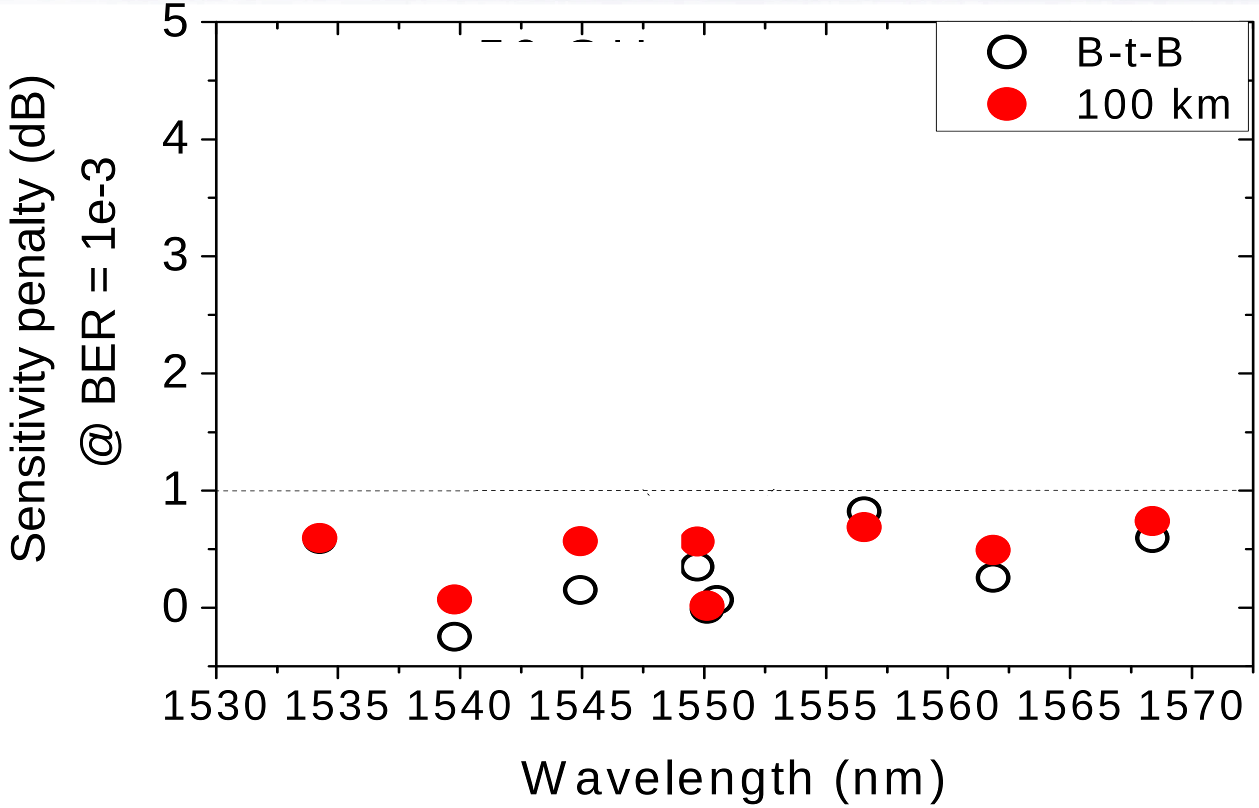
Coherent receiver using the hybrid laser as local oscillator





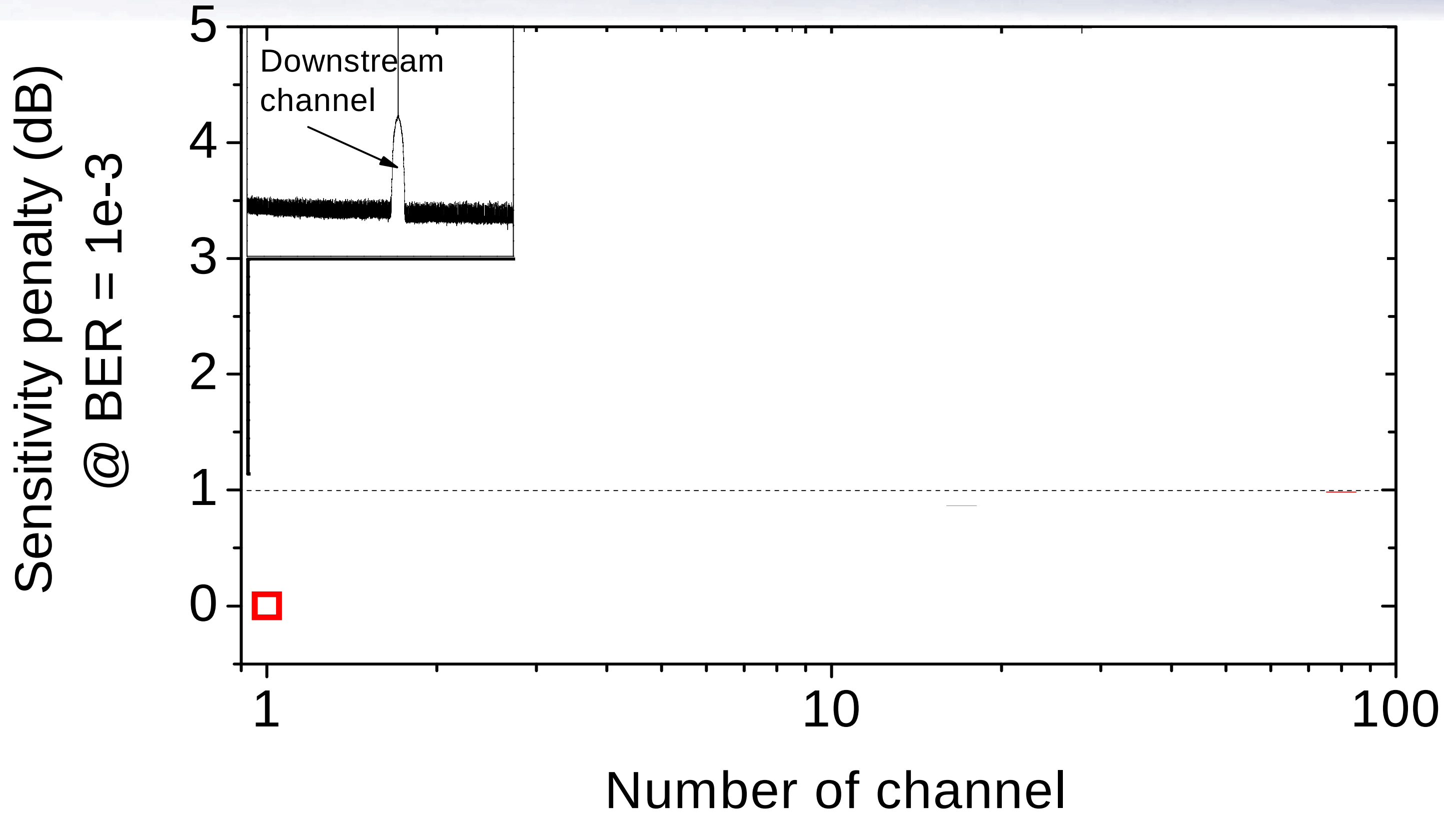
- **Power sensitivity of -27 dBm in b-t-b @ BER = 10^{-3}**
  - **No penalty compared to the reference laser (ECL)**
    - **No further penalty after transmission**
      - **Digital dispersion compensation in the receiver**

WDM operation over the C-band



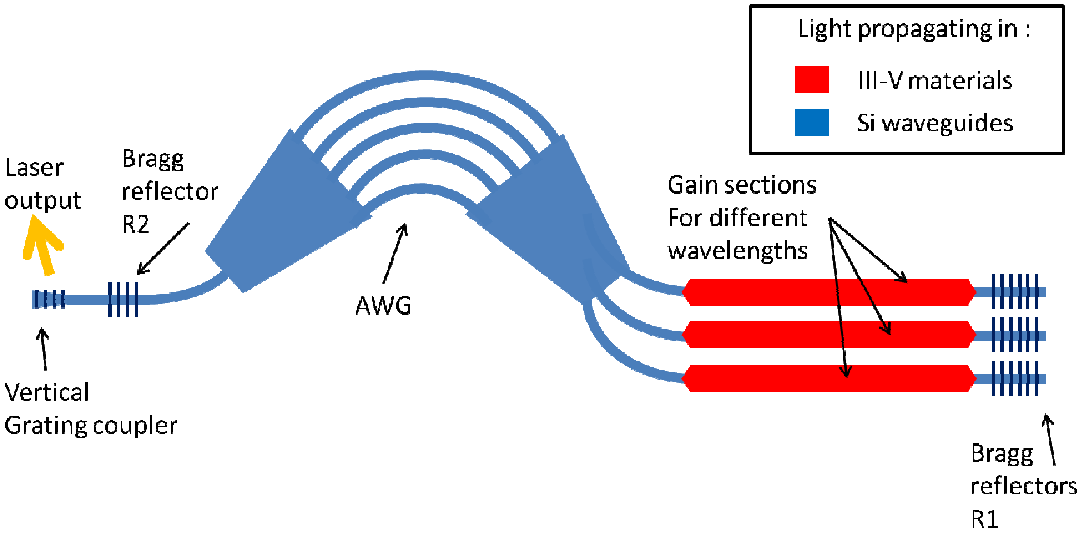
- **Sensitivity penalties with respect to the ECL**
- **Less than 1 dB channel-to-channel sensitivity across the C-band**
- **Consecutive wavelengths on the 50-GHz ITU grid**

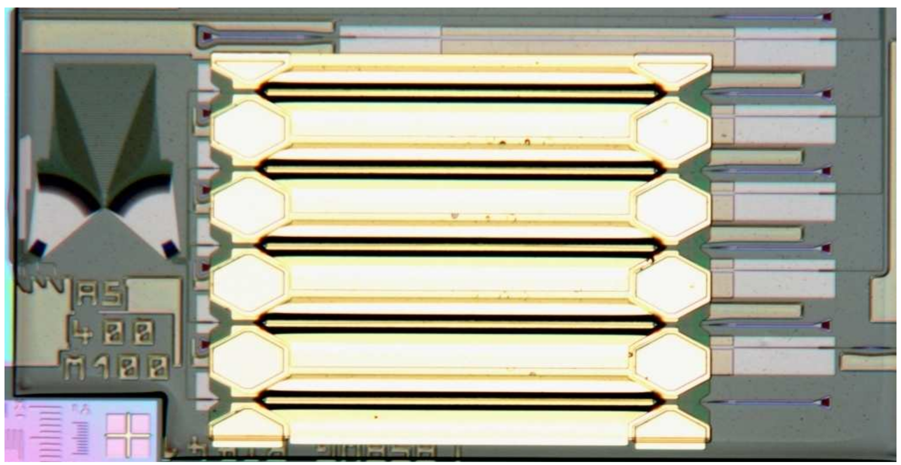
WDM operation with co-propagating channels



- **Number of neighboring channels up to a worst case of 80 (50 GHz)**
- **Possibility of filterless operation**

Wavelength selectable laser





Wavelength selectable source :

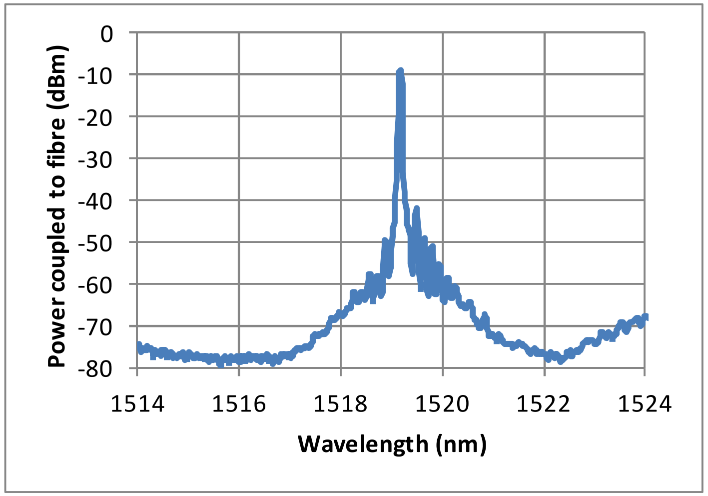
- Si AWG inside the laser cavity as a filter
- Broadband bragg reflectors for feedback
- Si AWG : 5 channels, 400GHz spacing
- Vertical bragg gratings for on wafer scale testing

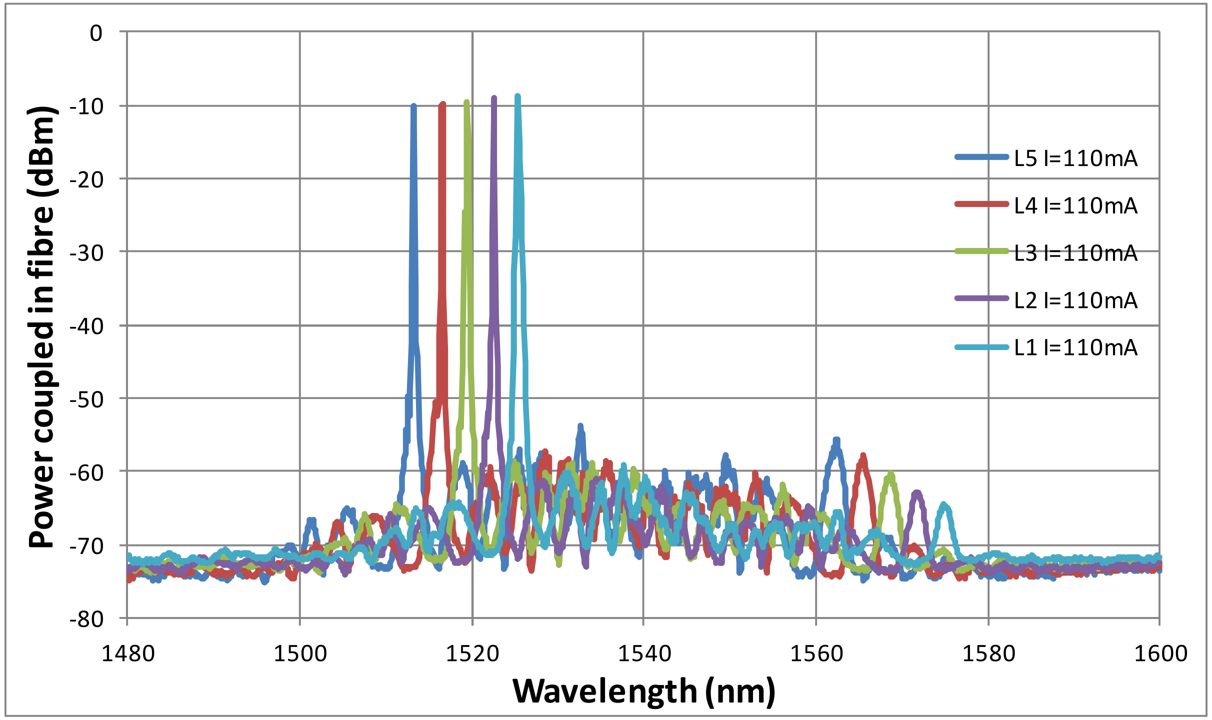
Simple wavelength tuning for access networks

Can also be used as multi-wavelength source

Wavelength selectable laser : spectrum

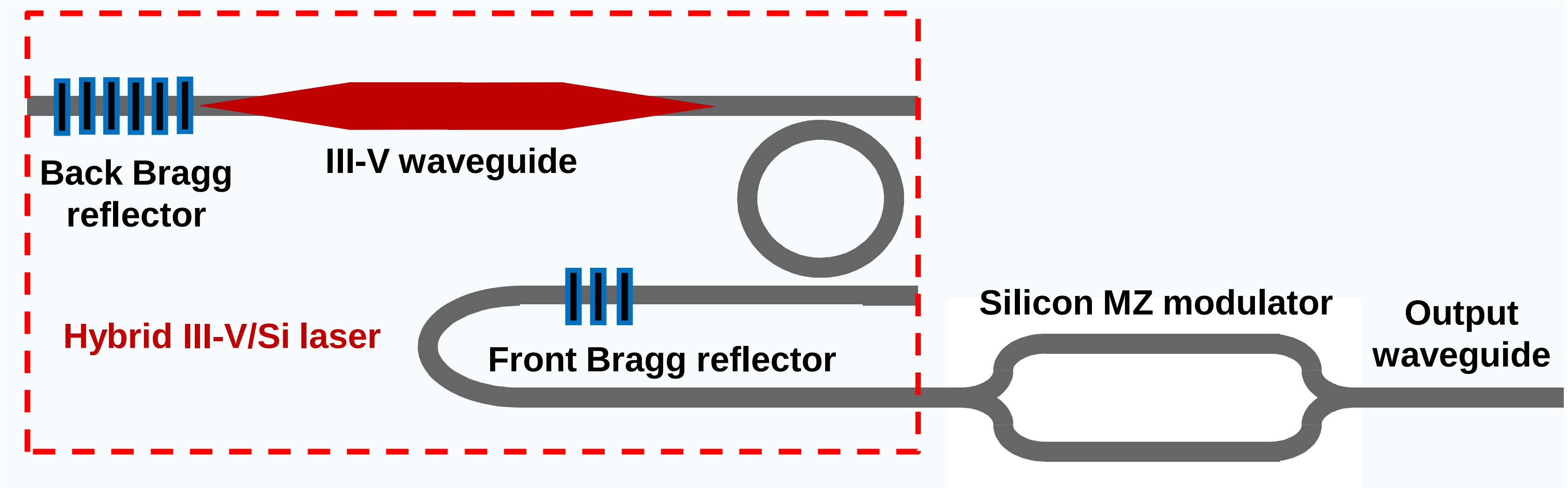
- Spectrum for each channel with 110mA injection
- Single mode operation with > 30 dB SMSR
- 390GHz spacing between channels

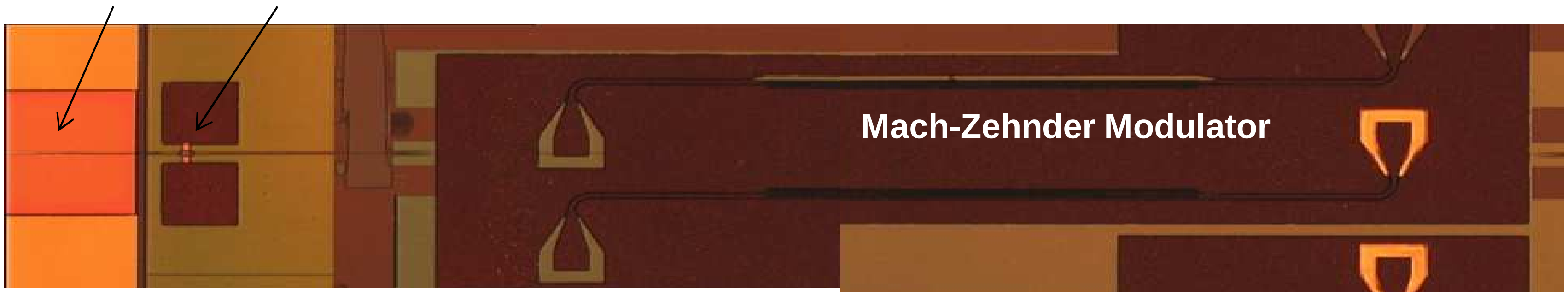




Spectrum for each channel

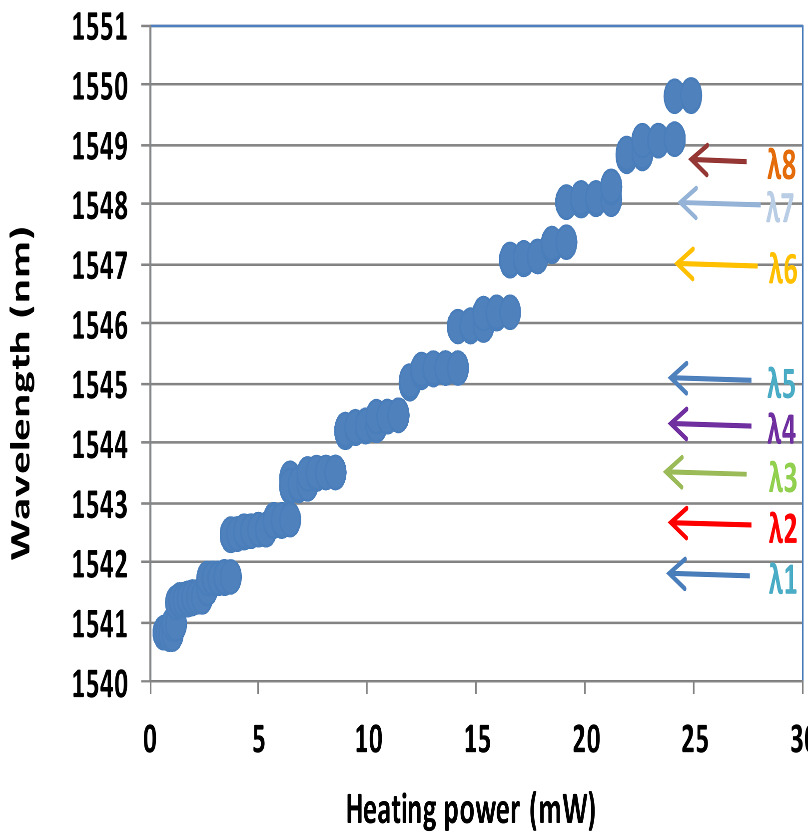
Tunable transmitter chip

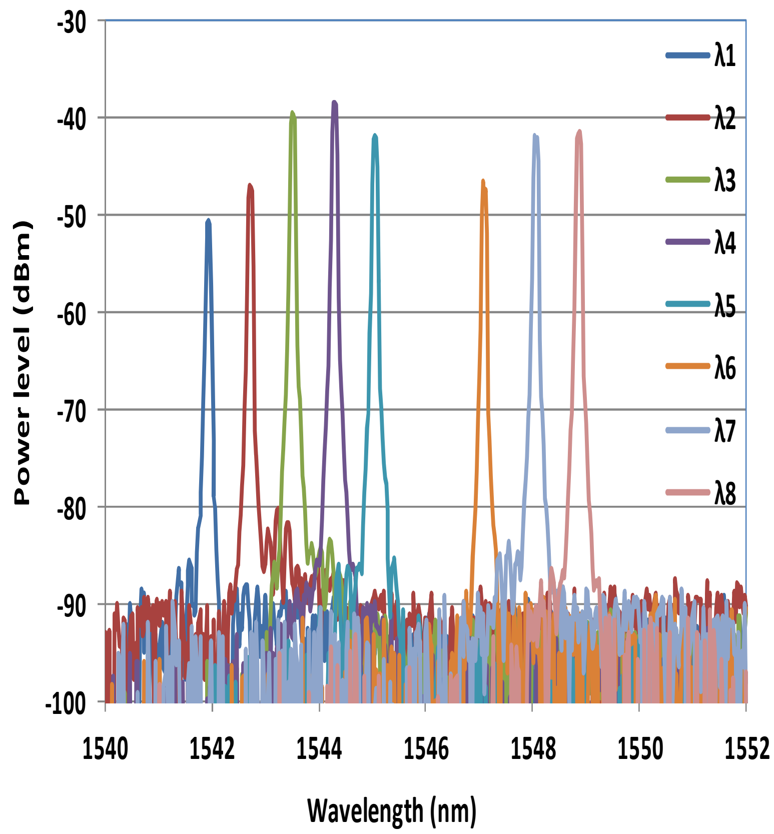




G. –H. Duan, et al., ECOC 2012

Wavelength tunability over 9 nm





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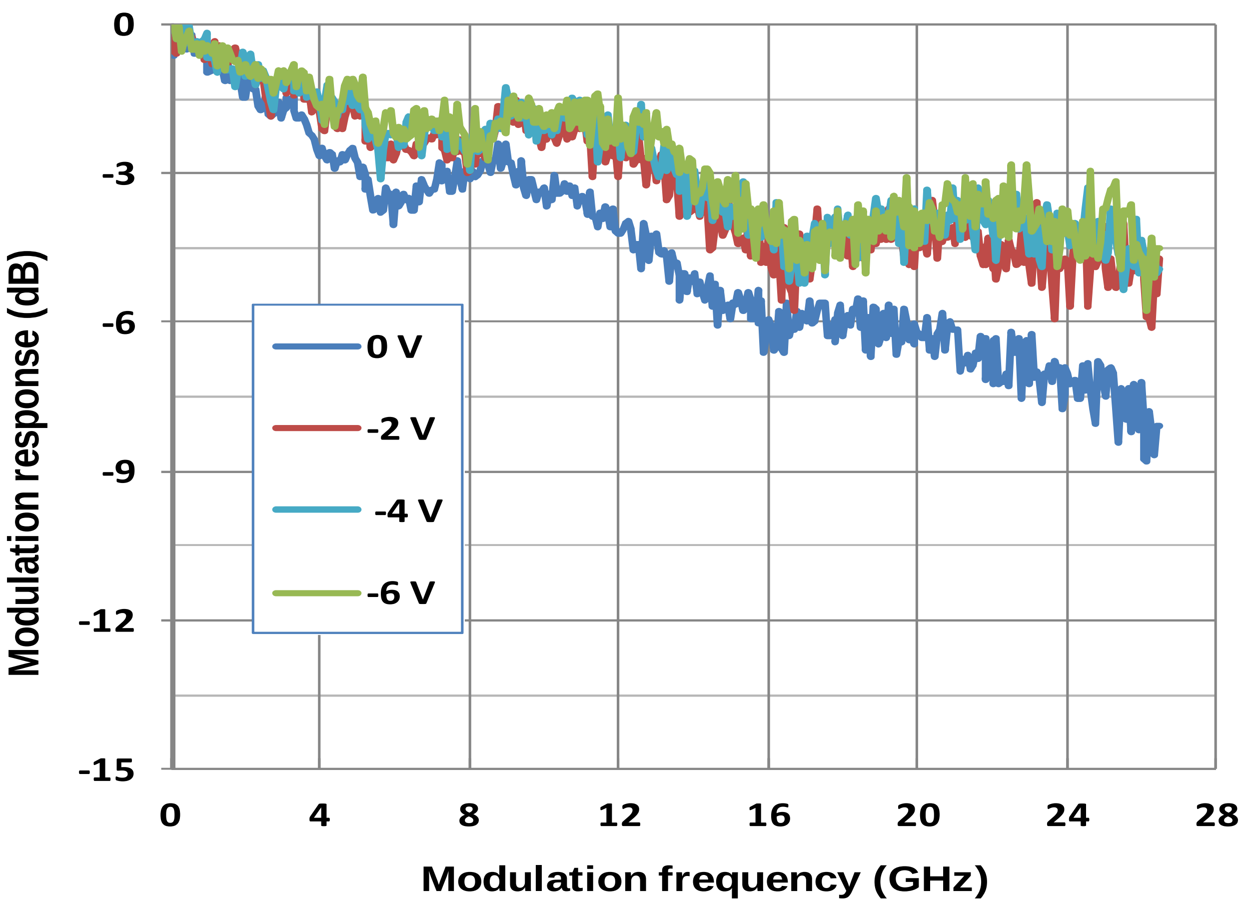
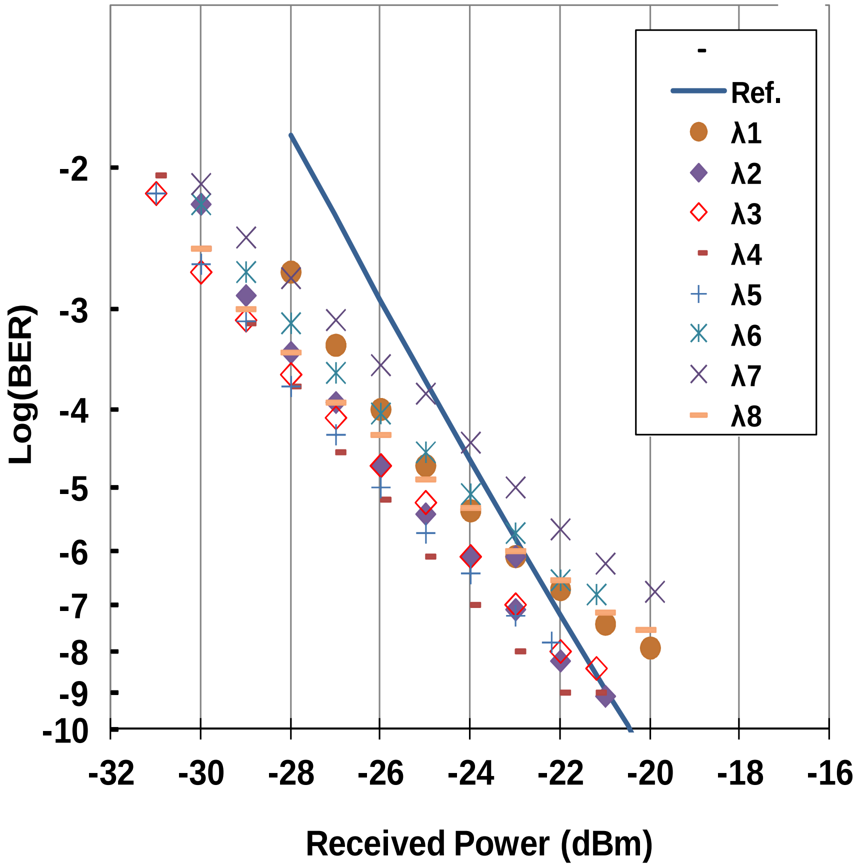
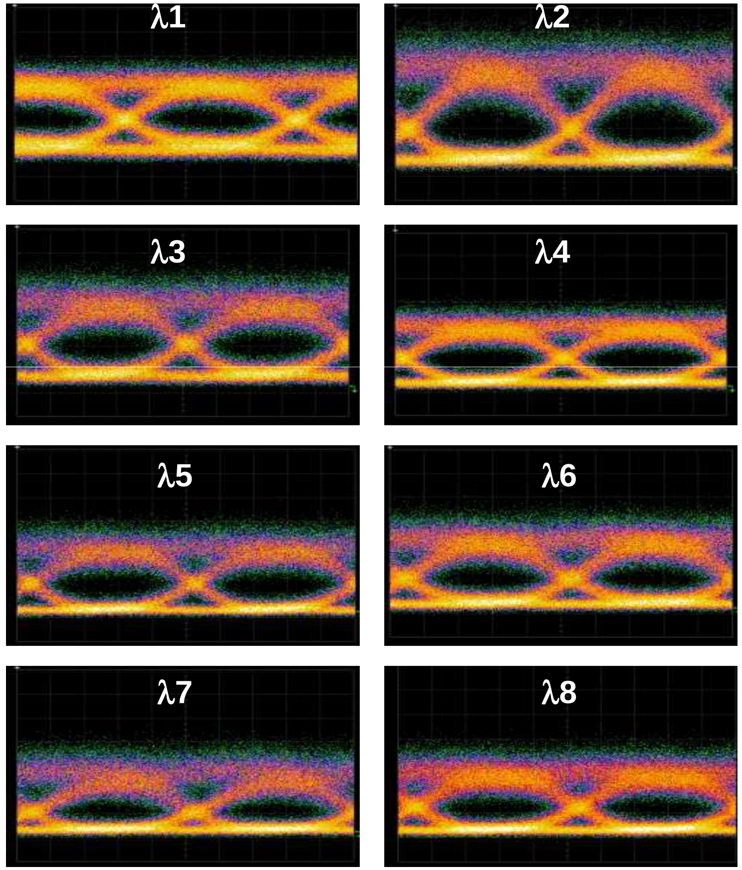
Si MachZehnder modulator



- **3 dB modulation bandwidth around 13 GHz**

BER and eye diagramme at 10 Gb/s





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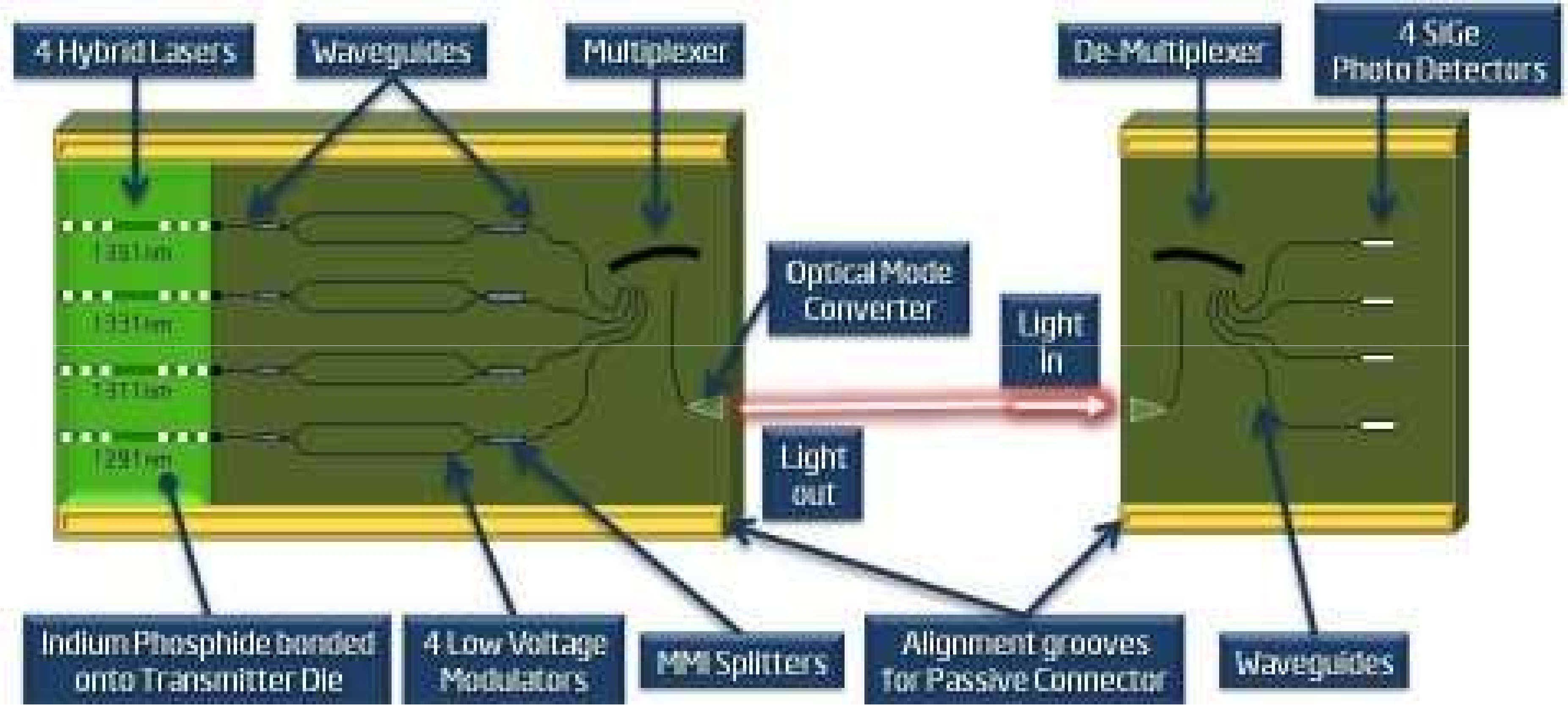
State of the art on hybrid III-V/Si lasers

	III-V Lab		LETI	Intel/UCSB			Monolithic InP lasers	
Type	Si FP	Si RRs	Si DBR	Si DBR	Si DFB	Si DBR	DFB	SG DBR
Silicon waveguide thickness (nm)	400	440	500	500	500	500	/	/
Ith (mA) at 20°C	30	21	40	45	25	65	< 20	< 20
η (mW/mA) at 20°C	0.1	0.1	0.1	0.1	0.05	0.15	> 0.25	> 0.25
Pmax (mW) at 20°C	18	10	14	30	5.4	11	30	20
SMSR (dB)	/	45	>20	/	40	40	40	35
Tunability (nm)	/	45	/	/	/	/	/	40
T° max operation	60°C	60°C	60°C	90°C	50°C	45°C	90°C	90°C
Wavelength (µm)	1.55	1.55	1.55	1.3	1.55	1.55	1.3-1.55	1.55

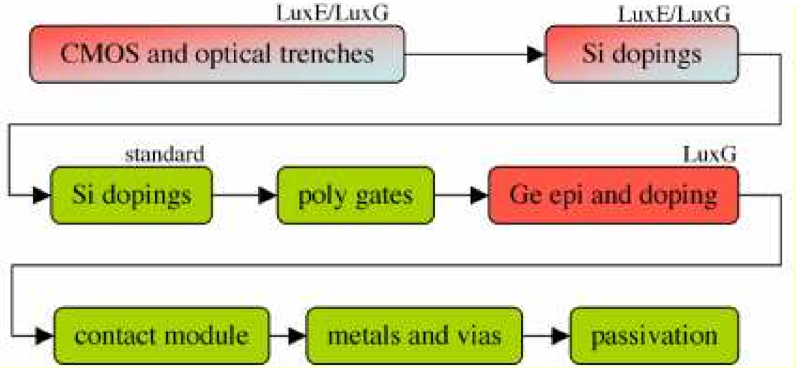
Intel's 4x12.5 Gb/s transceiver



Luxterra's Active Optical Cables

Luxtera technology for transceiver

- Freescale SC Hip7 0.13µm SOI CMOS process
- Customized SOI & CMOS 130nm technology →
- Proprietary library for electronic design
  - Flip chip laser die bonding
  - Si lateral depletion modulator ➔ 10Gb/s
  - Ge photodetectors ➔ 20GHz
  - Surface holographic gratings fiber coupling
  - 4x28 Gb/s using 4 parallel links

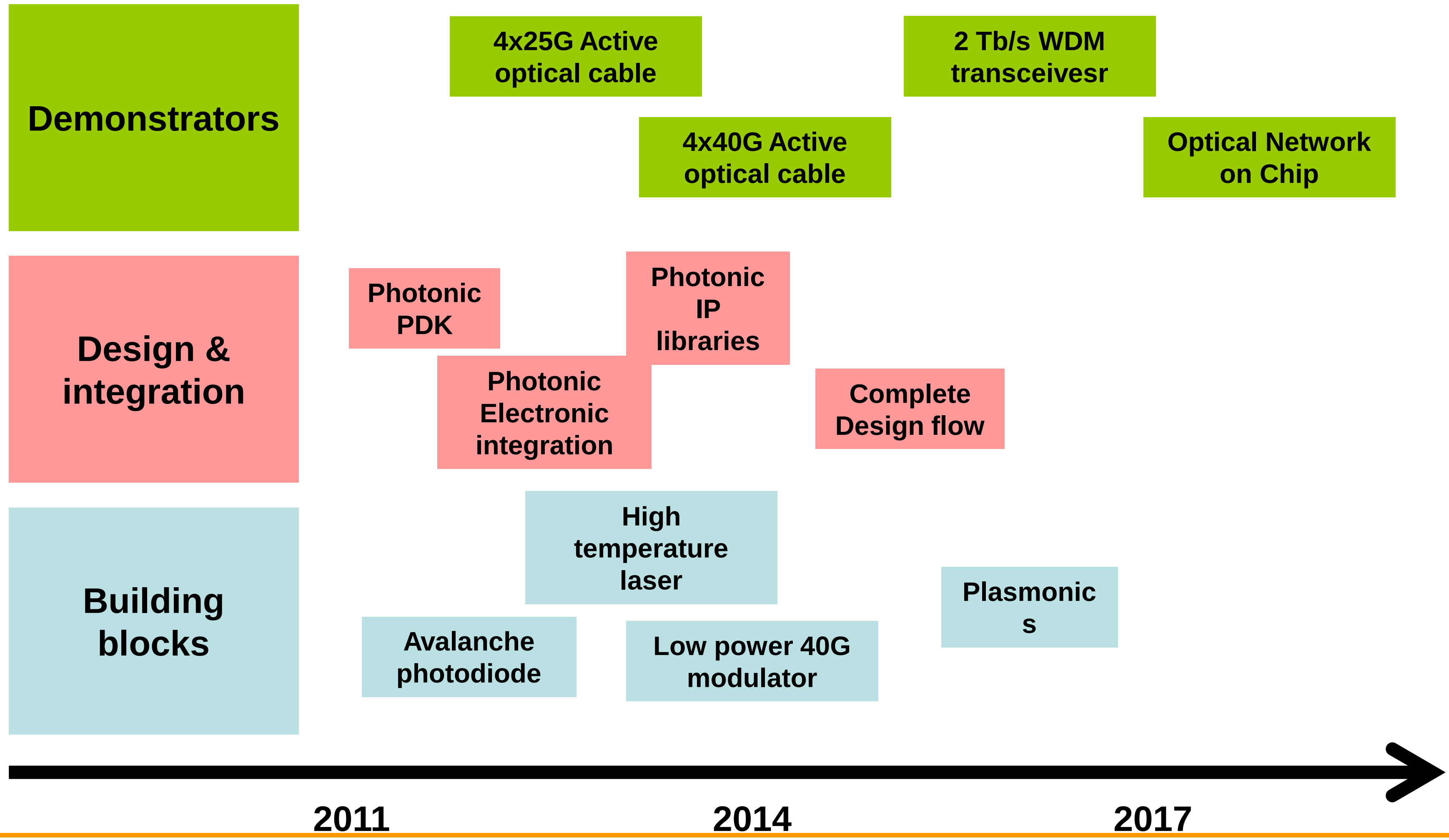


Luxtera and STMicroelectronics to Enable High-Volume Silicon Photonics Solutions

Collaboration between two leading companies will bring silicon photonics into mainstream markets

March 1st, 2012

Technology roadmap



III-V lab

La chaine de la valeur en photonique silicium

Materiaux	Equipements	Design Simulation	Fonderies	Integrateurs, Fabless	End-users
Soitec IQE	Replisaurus/SET EVG Agilent Cascade	PhoeniX Mentor Graphics Cadence Dolphin integration ARM	**ST** ALTIS LFoundry Globalfoundries Intel IBM	**ST** 3S Photonics OCLARO DAS Photonics Caliopa Intel, IBM, HP, Oracle Finisar, PMC-Sierra Altera Luxtera, Kotura, Genalyte Aurrion Skorpious	Bull Tyco Electronics IBM Alcatel-Lucent Thales FCI Radiall Ericsson Nokia Oracle Google Cisco

New start-ups?

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  - ANR SILVER (transceiver for access networks)
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- **Photonics Research Group, INTEC, Ghent University-IMEC**
  - S. Keyvaninia, G. Roelkens, D. Van Thourhout
- **School of Electronics and Computer Science, University of Southampton**
  - D. J. Thomson, F. Y. Gardes and G. T. Reed