A view on the Silicon Photonics trends and Market prospective

Jean Louis Malinge

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Outline

- ✓ *Introduction*
- ✓ *What do we call Silicon Photonics*
- ✓ *The need for Silicon Photonics/Photonics*
- ✓ *Silicon Photonics-the ecosystem (players-supply chain)*
- ✓ *Silicon photonics-the early commercial products*
- ✓ *What’s next? Roadmap and conclusion*

Introduction

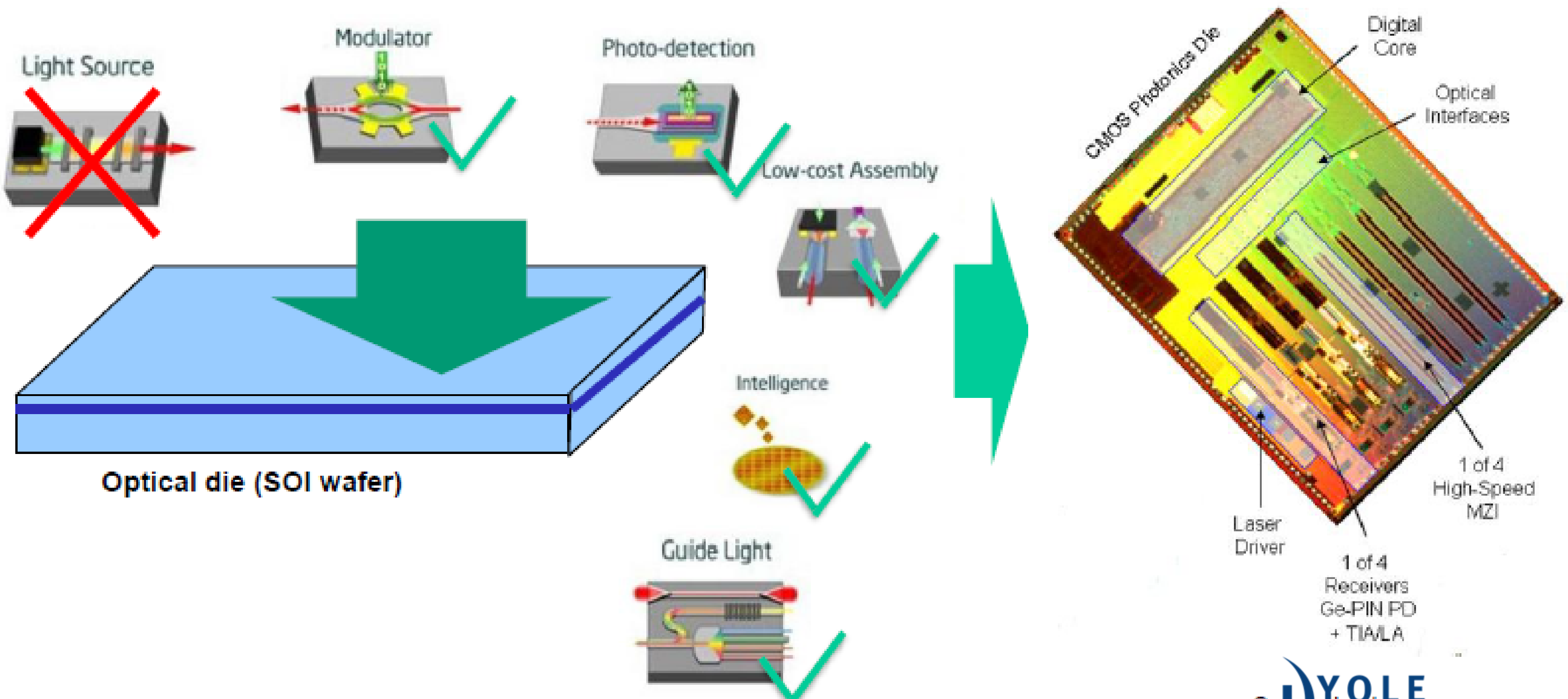
- ✓ My objective is to give you a broad overview of the Silicon Photonics trends and Market/application prospective
- ✓ Although the Silicon Photonics platform has been pioneered for 25 years this is still a technology in its infancy with a broad worldwide academic effort, numerous start-ups founded around the world and large corporations spending large R&D budget.
- ✓ This presentation was built from my experience as CEO of Kotura in California which I recently sold to Mellanox technologies **www.mellanox.com** and a contribution done in the last few months to a market analysis published by Yole Development **www.yole.fr** – **www.i-micronews.com**

What do we call Silicon Photonics ?

→ A disruptive technology: new breed of monolithic opto-electronic devices in a potential low cost Si process.

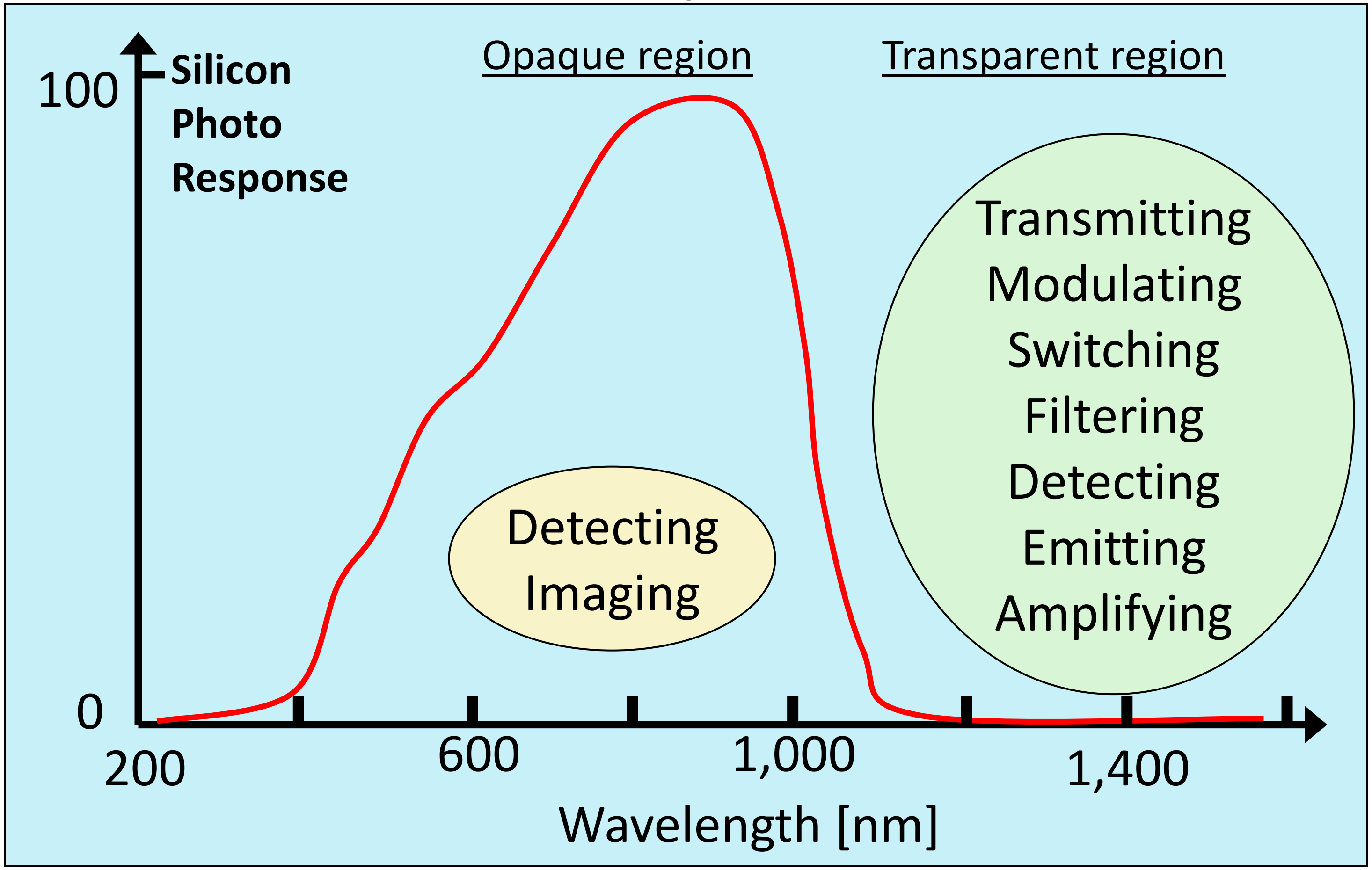
→ The vision: to deliver optical connectivity everywhere, from the network level … to chip-to-chip.

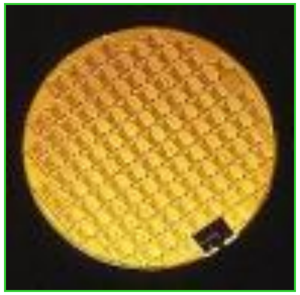
→ Today, except for the light source, many optical functions can be embedded at the SOI wafer level.

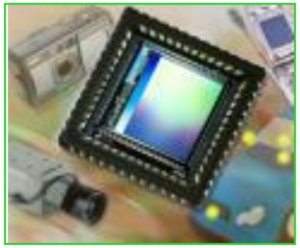


YOLE Développement

Silicon is widely used in optics and photonics





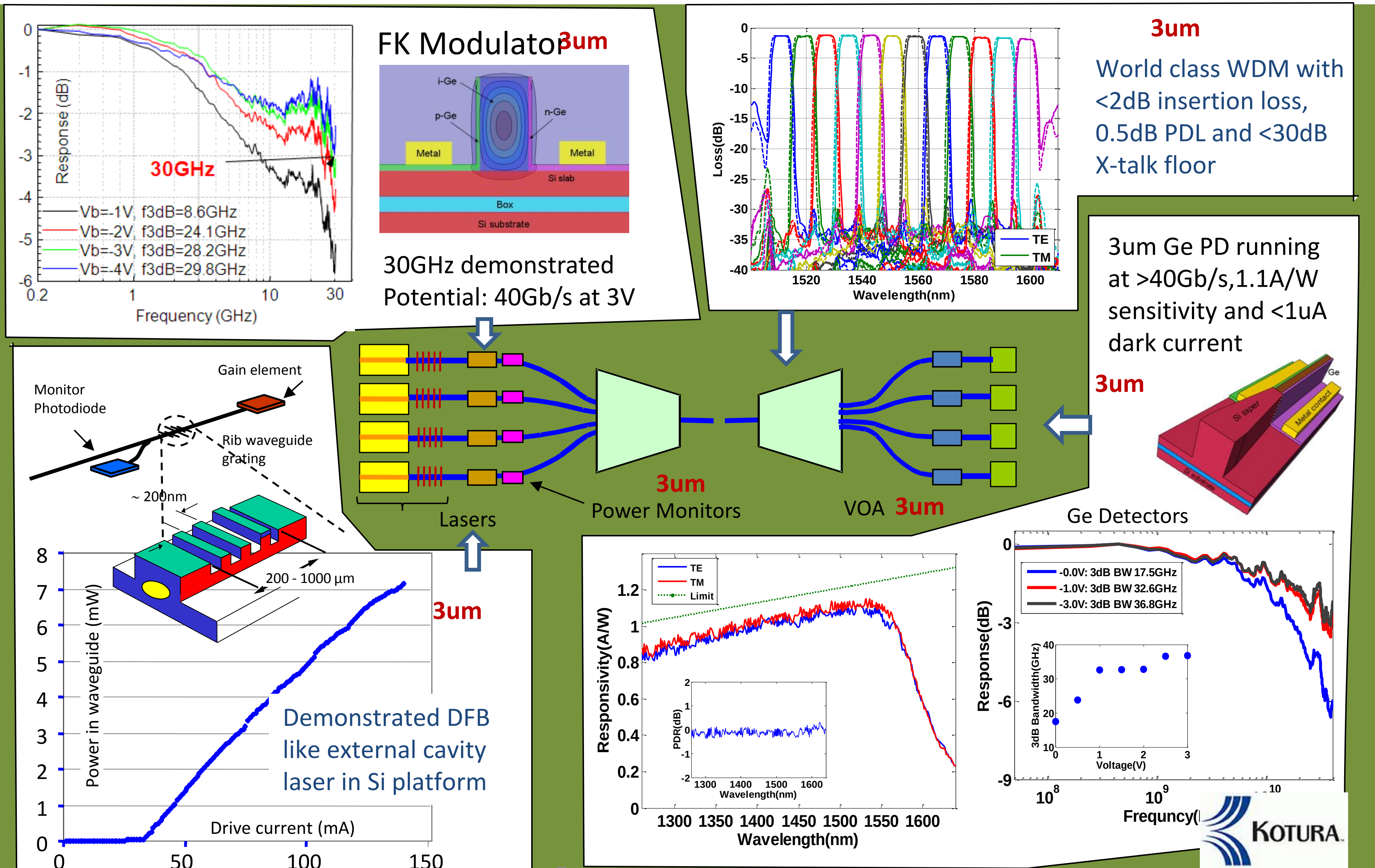


Building blocks overview

BRICK	TYPE	MAIN CHARACTERISTICS
LASER - LIGHT SOURCE	***Hybrid*** (Main approach)	Main approach today : III-V laser dies are bonded on a Si receiver die with 2 different approaches: ✓ Laser is integrated in a small bloc with the isolator and the coupling lens and then bonded to the Si die: main solution today used by Luxtera or Lightwire ✓ Laser die is flip chip bonded on the Si receiver: coupling guide, no isolator required: solution used by Kotura
	Monolithic	Light source is processed on SOI – but Si does not emit light - still basic R&D (2012)
	Off-chip	Use coupled external laser - multiple wavelengths, power / thermal management is independent but needs complex packaging / couplers / fiber attach
MODULATOR	***EAM ("Electro Absorption Modulators")***	Strong effect with both hybrid / monolithic approaches possible
	Phase modulators	External modulator – electro refraction is not mature (2012) while free carrier concentration variation modulation is the most effective mechanism today
	MZI (Main approach)	Mach-Zehnder Interferometer is commonly used but has high power consumption (>1pJ/bit) and is quite a long structure
	Resonators	Micro ring is still in R&D stage (HP main focus) – small size (down to 3µm), high speed (up to 30 Gb/s) and low power is possible
MODULATOR DRIVER	***ASIC***	Very complex analogic circuit (with few design players worldwide). 3 possible technologies depending on the signal power (CMOS, SiGe or III/V). Can thus be integrated on the transceiver substrate or as a separate die.
DETECTOR	***Attached***	Mature but low integration density, expensive (considered for chip-level photonics with IBM Holey Optochip for example)
	Hybrid	III-V dies/wafers are bonded – no alignment, high density but not fully integrated
	Monolithic (Main approach)	✓ Main approach today: Ge on SOI processed detectors. ✓ Si photo detectors (use of crystal defects, deposited polySi in µring resonators) are emerging as well. ✓ Large range of technologies possible.
MULTIPLEXER - MUX & DEMUX	***Grating***	Used by Kotura
	AWG (Main approach)	Most popular in Telecom
	Ring resonator	Can be used for both Mux/Demux but manufacturing is challenging and ring resonator is very sensitive to thermal variations
COUPLERS	***Evanescent, grating, inverted taper etc …***	Allows fiber-to-chip or intra-chip coupling. Gratings on Si are today mostly used.

OTHERS	***Waveguides, splitters, Trans Impedance Amplifier (TIA)…***	✓ SOI is well suited for waveguide because of high difference in refractive index.
		✓ Different technologies: Rib/ridge WG, Strip/Wire WG, photonic crystal WG, Slot WG
		✓ Different waveguide dimensions/technologies:
		    ✓ 3 µm x 3µm with Kotura. Bigger waveguide meaning higher signal power handled. Interesting approach for transceivers. Electronic and Optics functions are independent, need for bonding or via technology to connect both.
		    ✓ 0.4 µm x 0.4 µm by Luxtera. Historically for better electronic & photonic integration and easier manufacturing

From Building Blocks to a Complete Platform



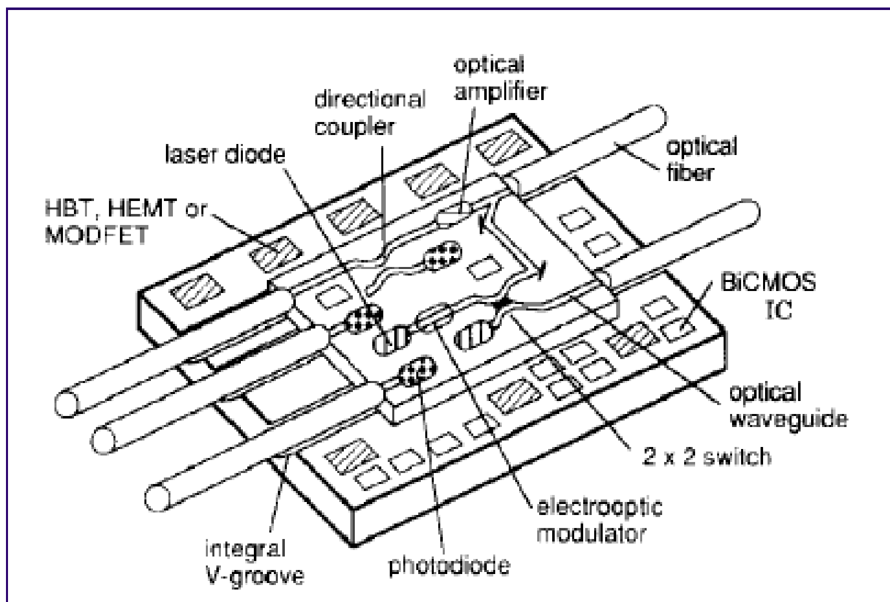
Si Photonics: An Industry 25 Years in the Making

Dr. Richard Soref (USAF) pioneered Si photonics in the '80s

"…single-crystal Si will be suitable for building directional couplers, filters, star couplers, optical switches, mode converters, polarizers, interferometers, and modulators that operate at $\lambda = 1.3$ or $1.6\ \mu m$ (and beyond)-essentially every integrated-optical component except an optical source. The use of Si for photodetection at $1.3\ \mu m$ has also been suggested."

R. A. Soref and J. P. Lorenzo, J. Quant. Electron. **22**, 873 (1986)

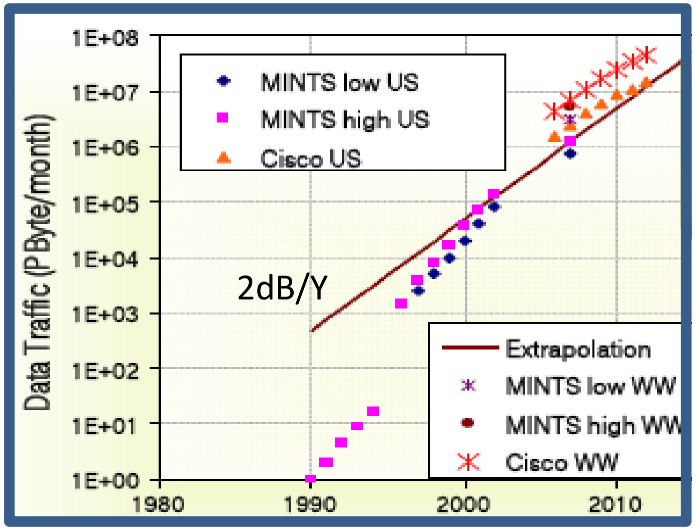
Fundamental work developing silicon waveguides between 1985-1989



Silicon-based "superchip" Proposed by Soref, 1993.

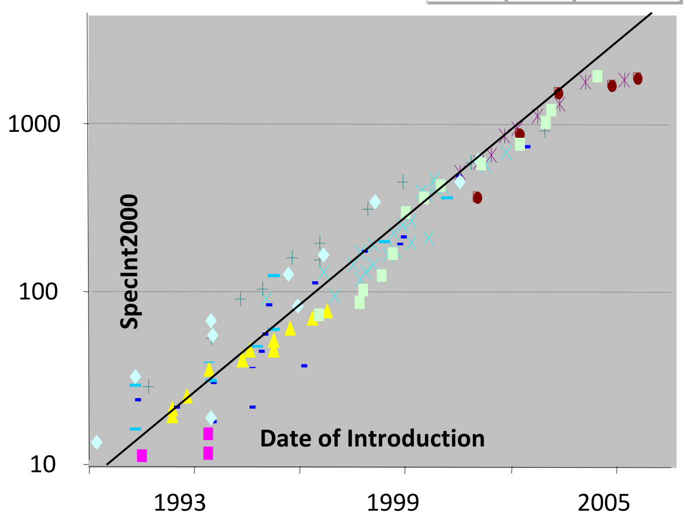
The Need for Photonics

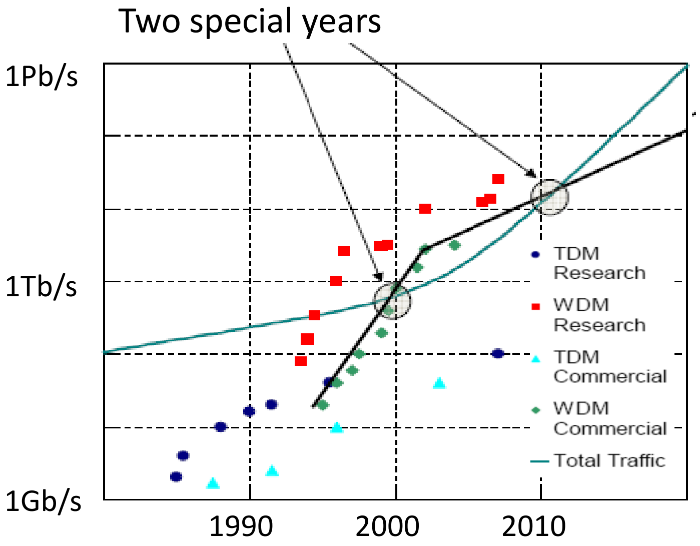
- The information explosion. We Created:
  - 5 EB by 2000, ~500EB by 2009 & 2500 EB / year by 2012
  - Use of internet for entertainment and broadcasting on demand
- Rapid growth in internet traffic is driving growth in computation and communication of information.
  - Huge challenges on processing, transmission and storage
  - 2dB/Y of demand met by 1dB/Y growth



Prefix	Sym	Decimal
exa	E	1E+18
peta	P	1E+15
tera	T	1E+12
giga	G	1E+09

- Convergence of Computing and Communication
- Huge challenges to Moore's Law
- Dominance of power and energy!





What’s happening during 1 Internet minute

Battle between Optics and Copper

- ✓ ***Latency***
- ✓ ***Bandwidth***
- ✓ ***Power dissipation***
- ✓ ***Electromagnetic interference***
- ✓ ***Signal integrity***

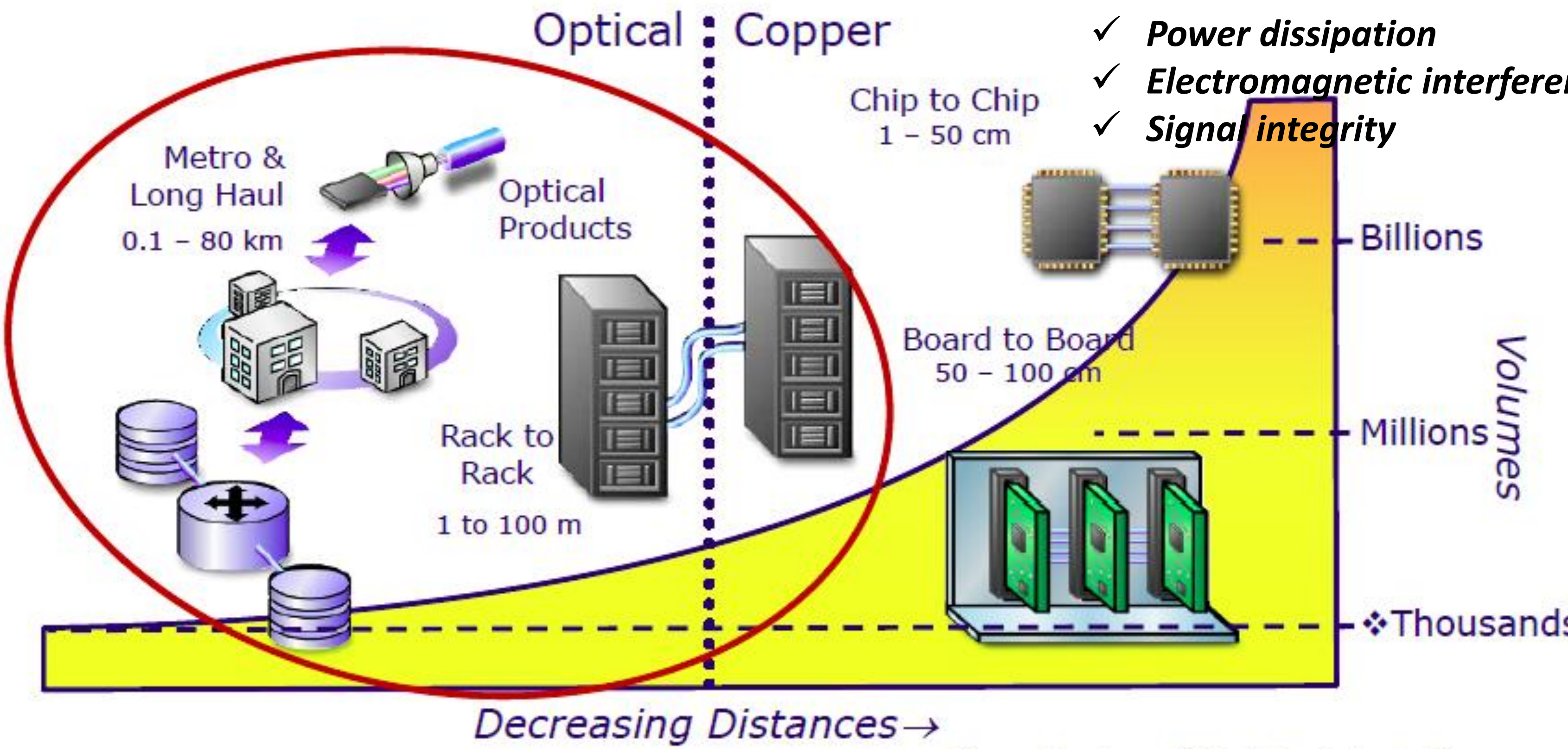
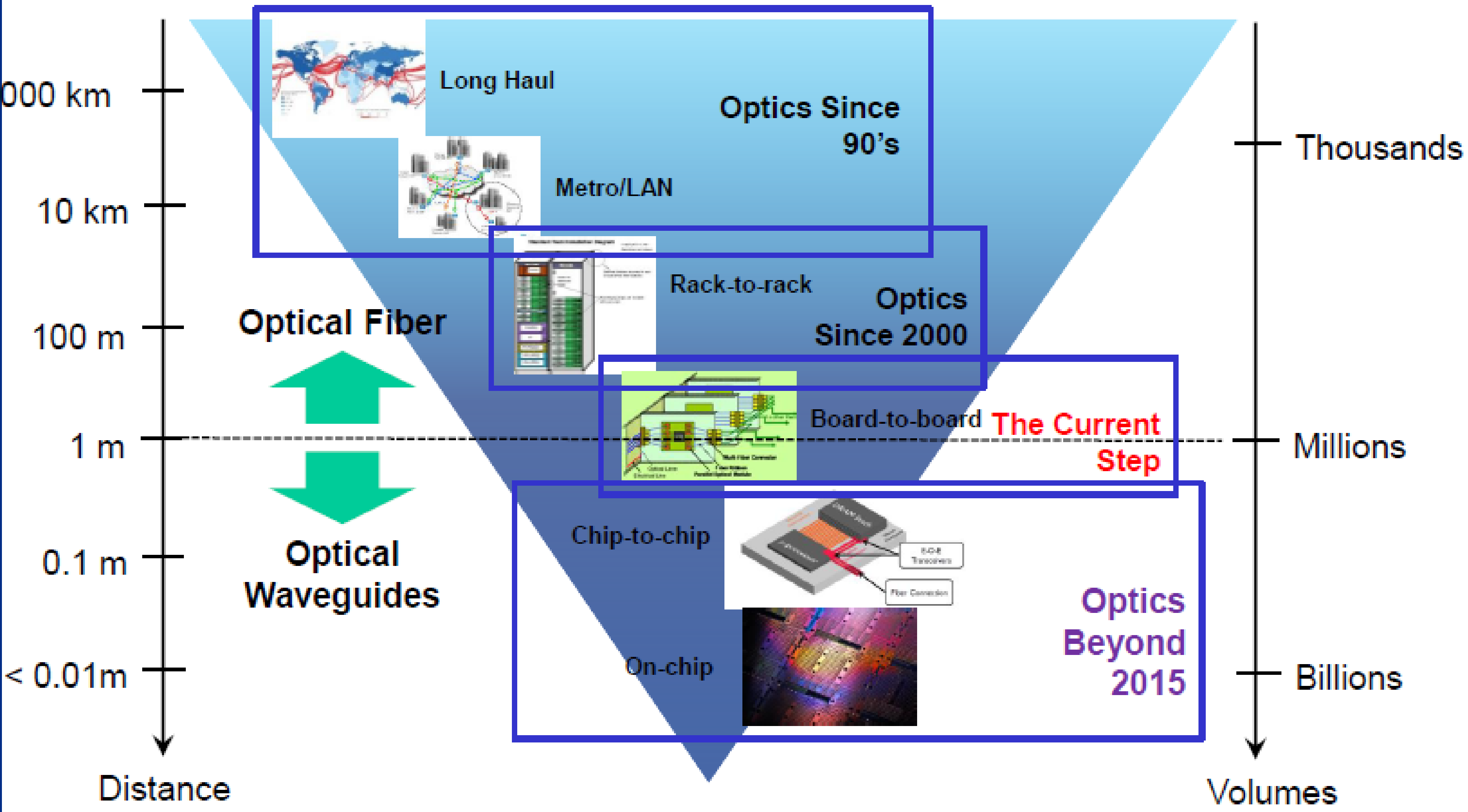


Figure Courtesy of Mario Paniccia, Intel

Optics has progressively eliminated copper in the metro and long haul network in the last 20 years and will continue its migration all the way to chip to chip application in the next 20 years

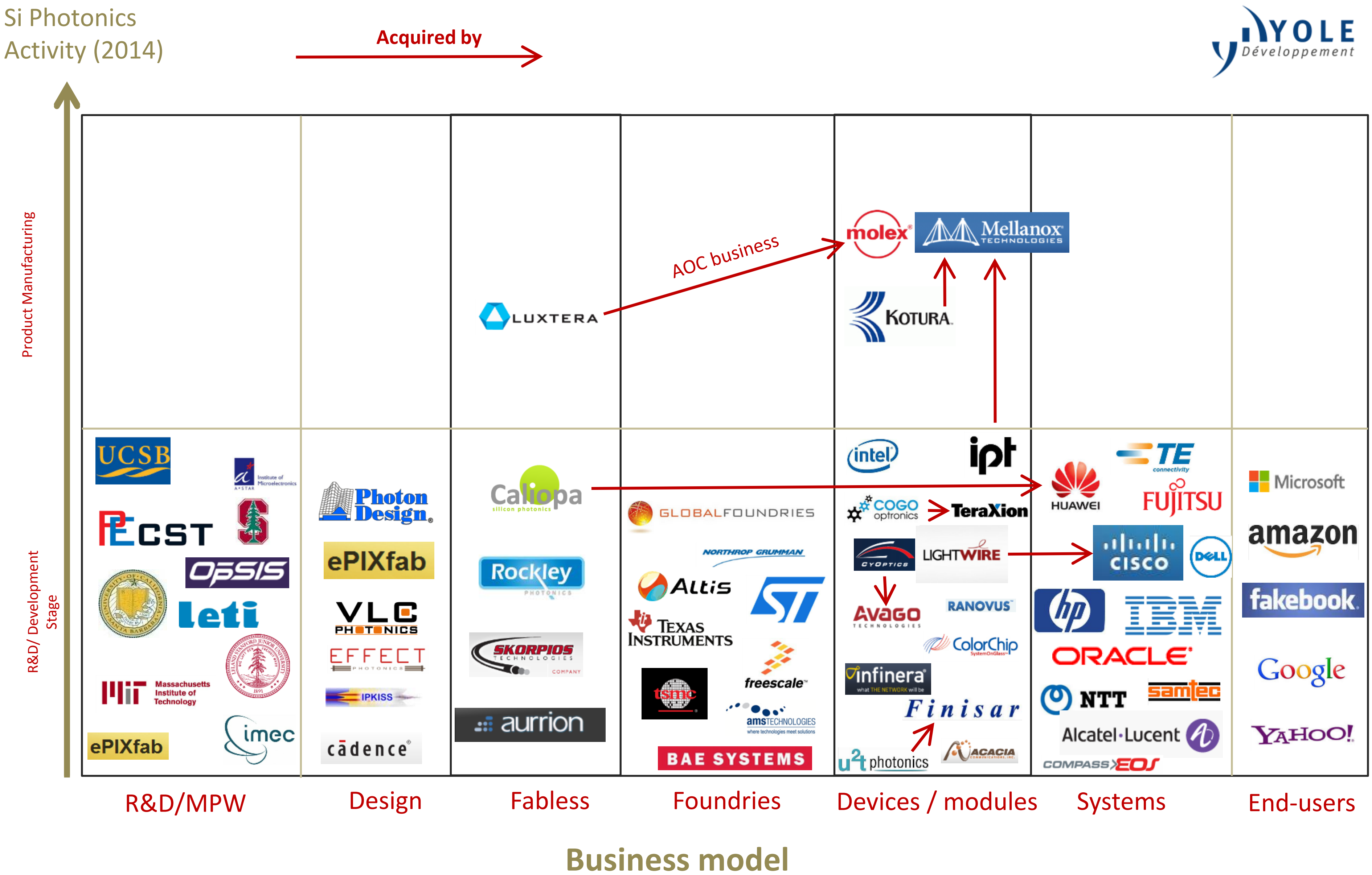
Optical Interconnects



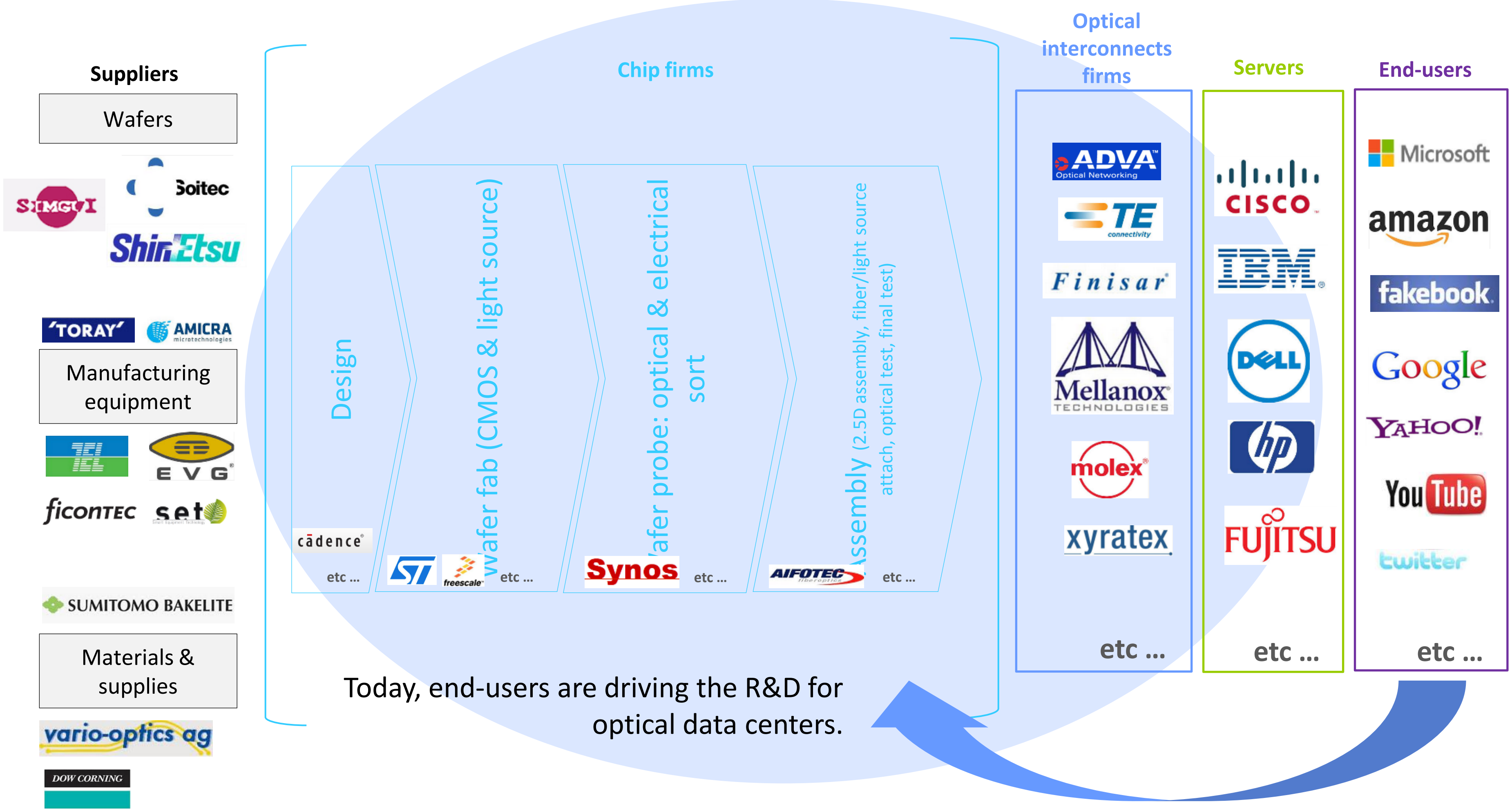
Silicon for Photonics components: the good and the not so good!!

- Transparent in 1.3-1.6 μm region
- CMOS compatibility
- Low cost
- High-index contrast – small footprint
- − High index contrast –waveguide loss
- − No detection in 1.3-1.6 μm region (in bulk Si)
- − No linear electro-optic effect
- − No efficient light emission

Supply chain: the ecosystem?



The Si Photonic supply chain



More than $1B invested worldwide by public fundings !

- **Strong investment from the European Commission**

  ✓ In the period 2002–2006, around **50 photonics research projects** were funded under the EU's 6th research framework program (FP6) for approximately **€130 million**.

  ✓ Since the beginning of FP7, **65 R&D photonic projects**, including organic photonics, have been selected so far with more than **€300 million** of EU funding.

  ⇒ **A total of €430 million invested by the European Commission e.g. US$ 580M**

- **Japan : JISSO program**
  ✓ $300M invested in 10 years

- **US : mainly DARPA programs**
  ✓ A $44M DARPA program involving Kotura, Oracle, Luxtera, various Universities (Stanford, San Diego)
  ✓ Orion also has a big program

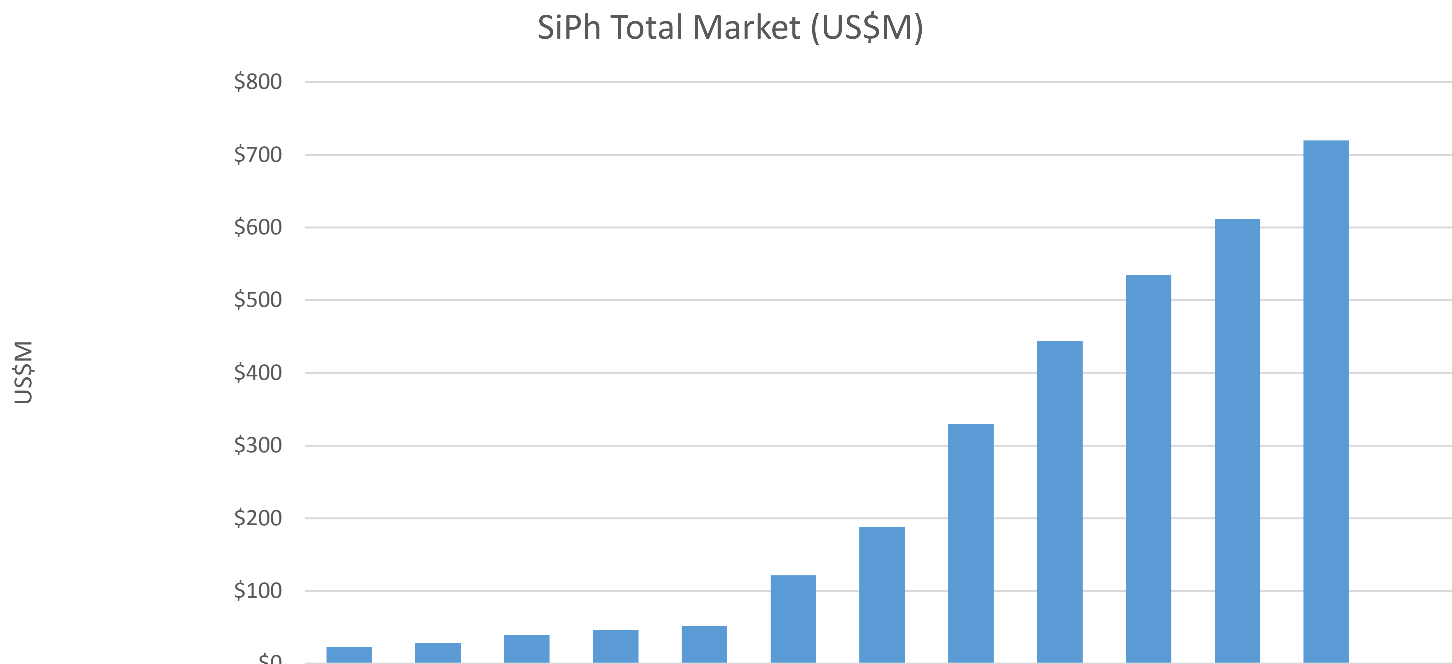
YOLE Développement

Almost $1B transactions for photonics in datacenter!

Company	Date	Product	Transaction value	Acquirer	Rationale for transaction
Lightwire (US)	February 2010	Silicon CMOS optoelectronics interconnects / optical transceivers.	**US$271M**	**Cisco** (US)	To face with increasing traffic in data centers / service providers
Luxtera AOC line (US)	January 2011	AOC line	**US$20M**	**Molex** (US)	Luxtera may be changing strategy to become an IP licensing company. Molex had AOC product line for 12-channel AOCs with a product from Furukawa/Fitel based on a 1060nm InGaAs VCSEL.
COGO Optronics (CAN)	March 2013	InP modulators & lasers.	**Est. < $30M**	**TeraXion** (CAN)	To access 100Gb InP modulator technology.
Cyoptics (US)	April 2013	InP-based photonic components.	**US$400M**	**Avago** (US)	To strengthen products portfolio for 40Gb & 100Gb data centers applications.
Kotura (US)	May 2013	Si photonics & VOAs for data center.	**$82M**	**Mellanox** (US)	To access 100Gb optical engine for data centers.
IPTronics (US)	June 2013	IC for parallel optical interconnects (drivers).	**$47M**	**Mellanox** (US)	To access products / technologies for 100Gb optical engine.
Caliopa (BE)	September 2013	Si-based optical transceivers for datacoms.	**$20M**	**Huawei** (CHINA)	To develop European-based R&D in Si photonics.

TOTAL: ~US$900M
Est. 2013 Market < US$30M

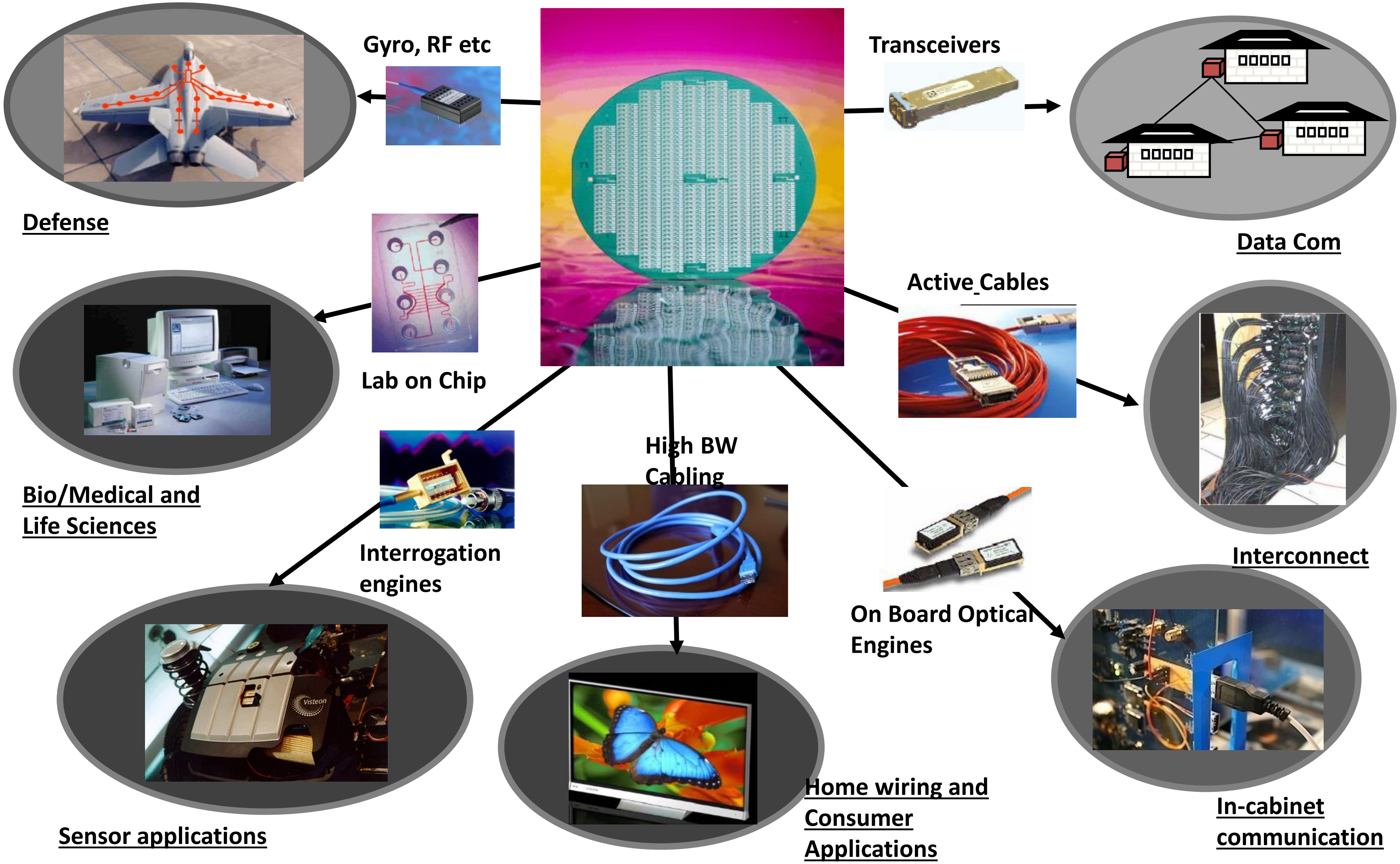
Silicon photonics 2013-2014 market forecast in US$M



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	CAGR
SiPh Total Market (US$M)	$23	$29	$39	$46	$52	$122	$188	$330	$444	$535	$612	$720	38%

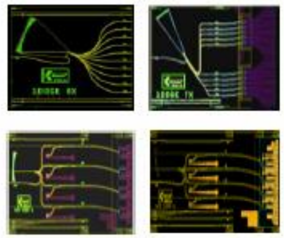
- **Silicon photonics devices market will grow from less than US$25M in 2013 to more than US$700M in 2024 with a 38% CAGR.**
  - Emerging optical data centers from big Internet companies (Google, Facebook …) will be triggering the market growth in 2018 (see following slides).

A broad range of application



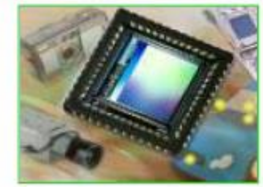
Kotura products

Ethernet for WAN

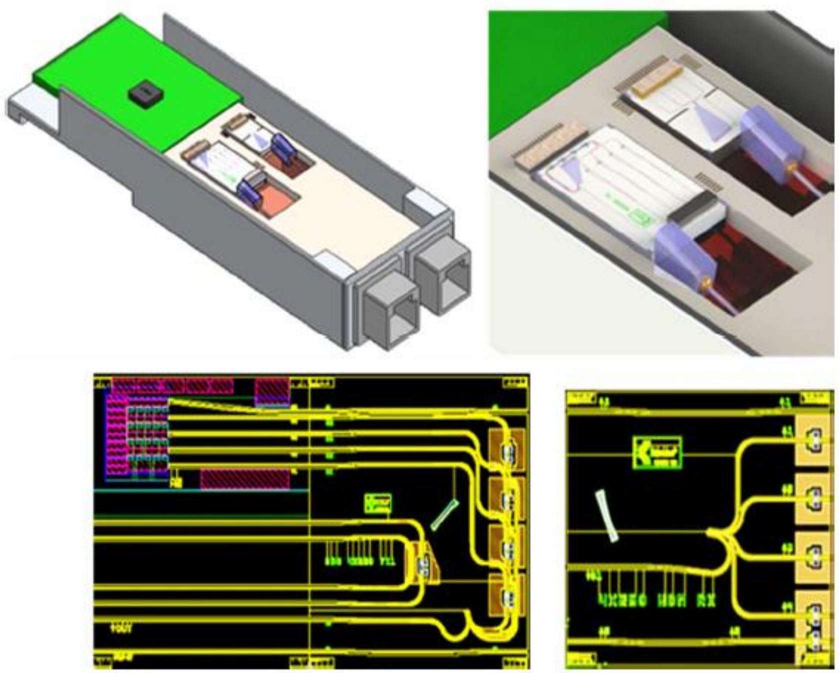


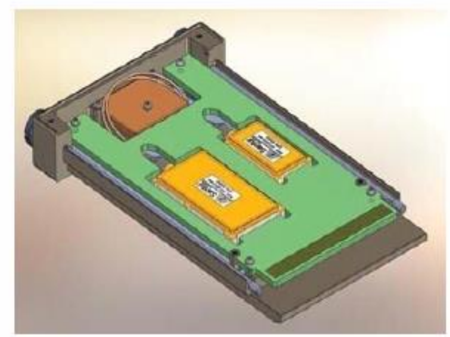
4x25G QSFP Transceiver

Pluggable Board Optics Transceivers

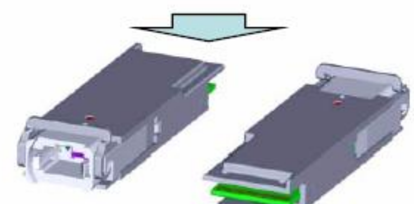


Optically Enabled Multi-chip Modules



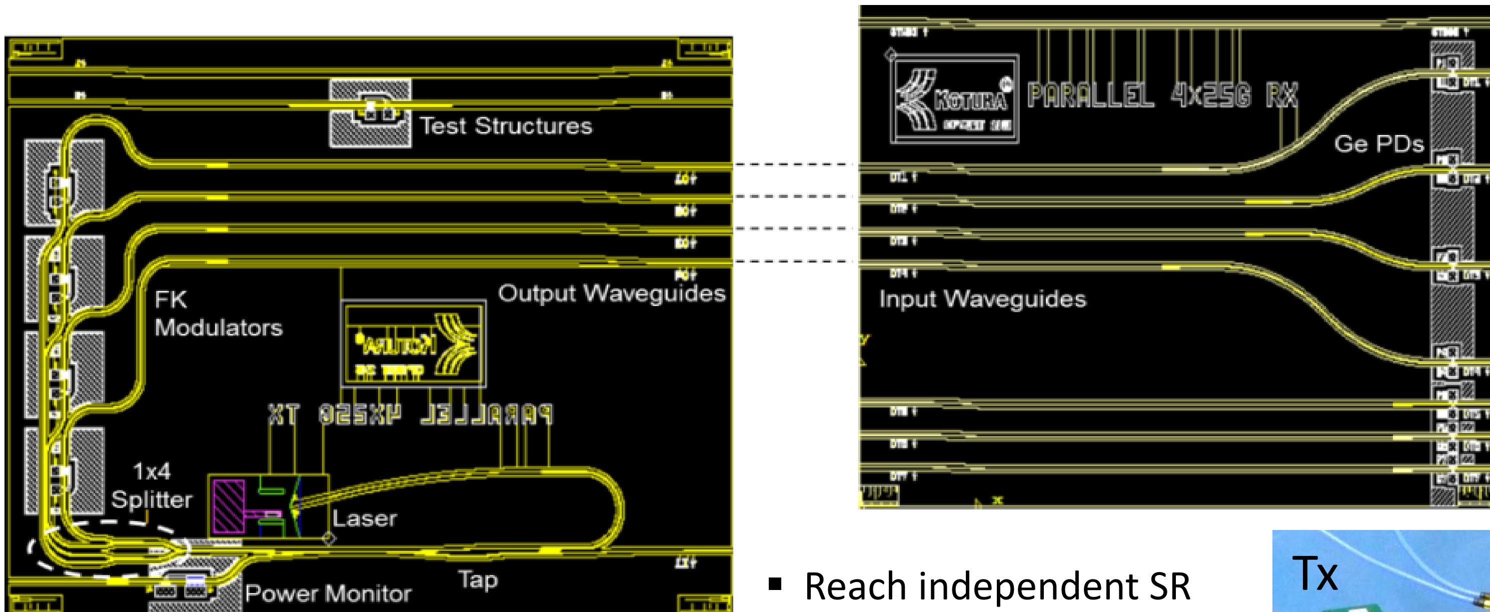


Competitive solution based on CFP package achieves **400Gbps** panel density



Kotura solution based on QSFP footprint will provide a record **4.4Tbps** panel density

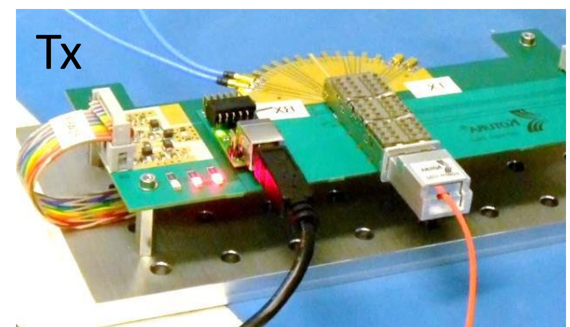
4x25G QSFP Parallel Link



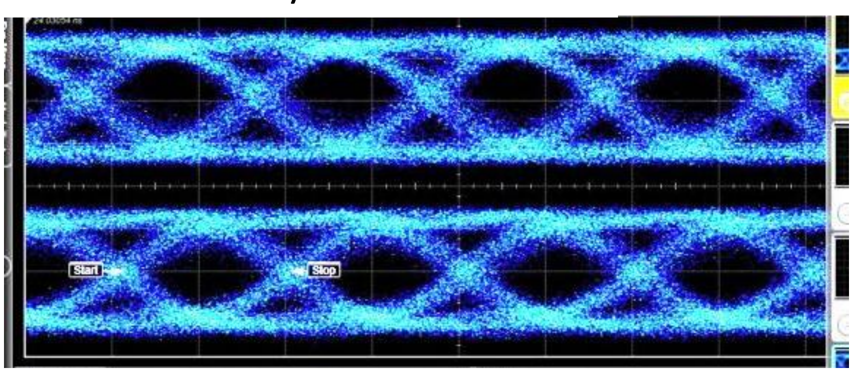
- Current: ~1.5W
- Next gen: 0.8W
- Assuming no CDR
- SMF low jitter

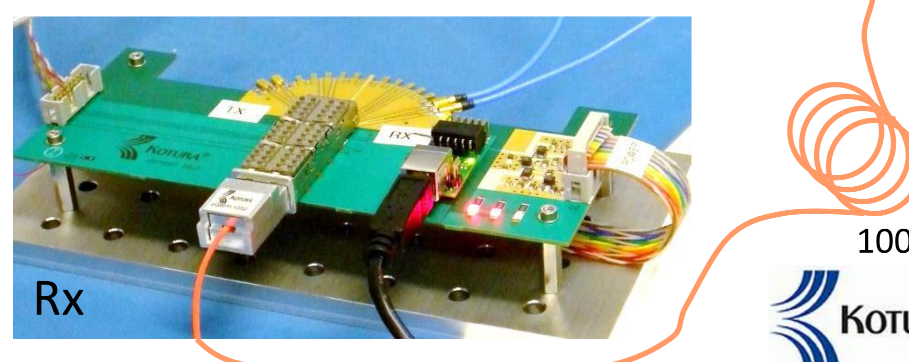
- 4x25G Parallel in QSFP

- Reach independent SR transceiver or AOC solution
- Reliable Edge emitters

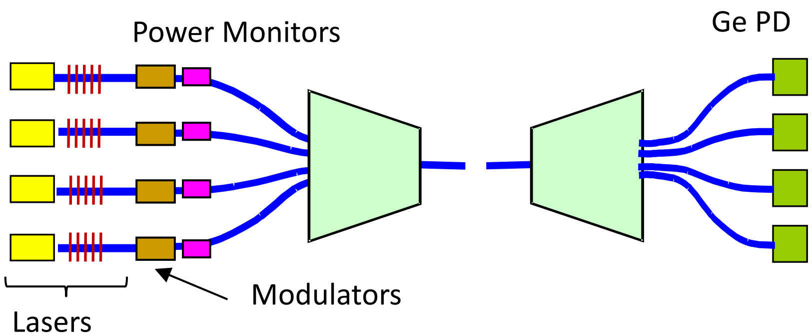


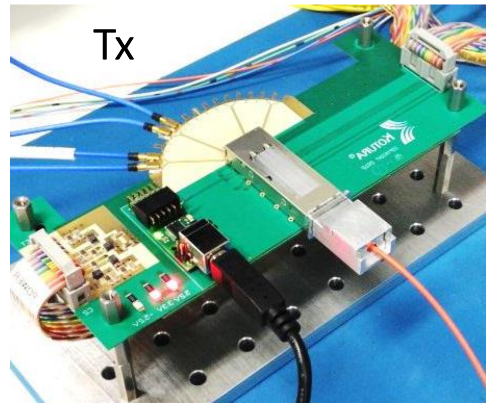
Differential Rx Eye at 25Gb

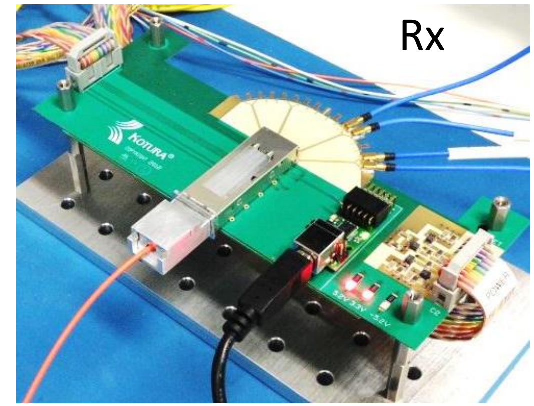


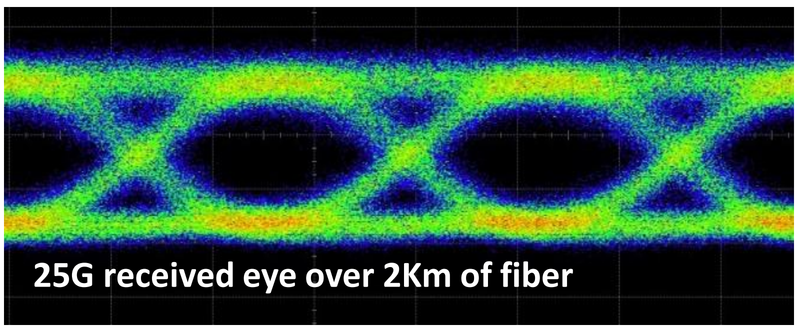


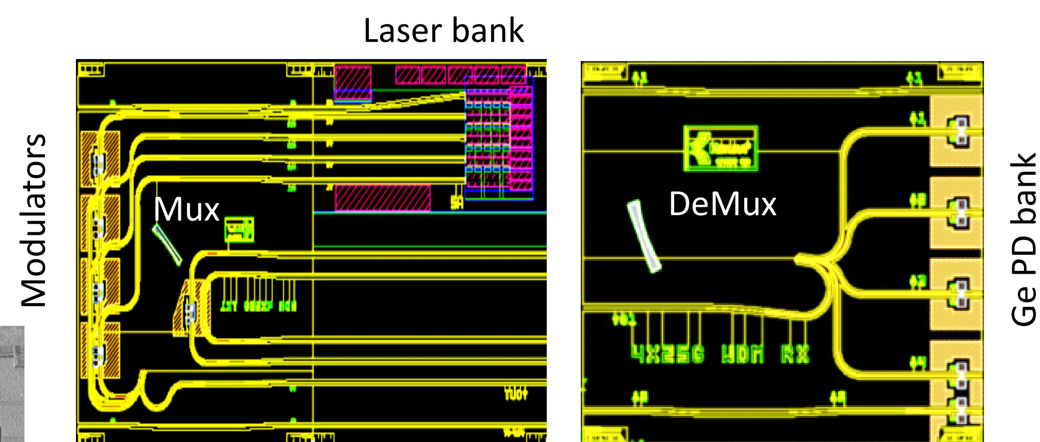
100GbE (4x25G) WDM in QSFP

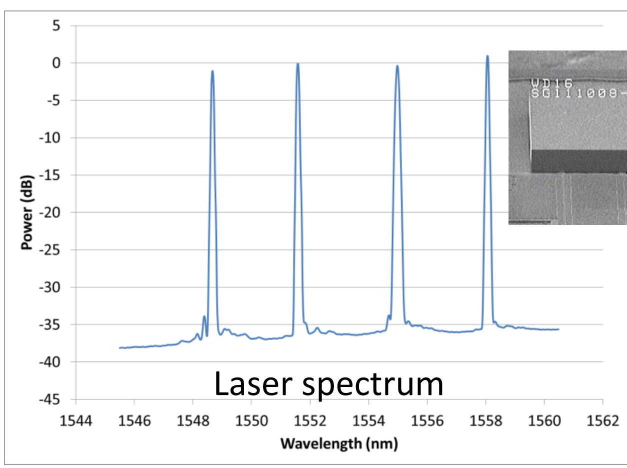


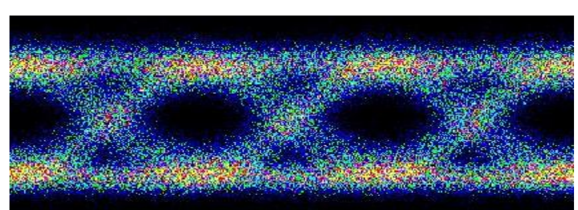








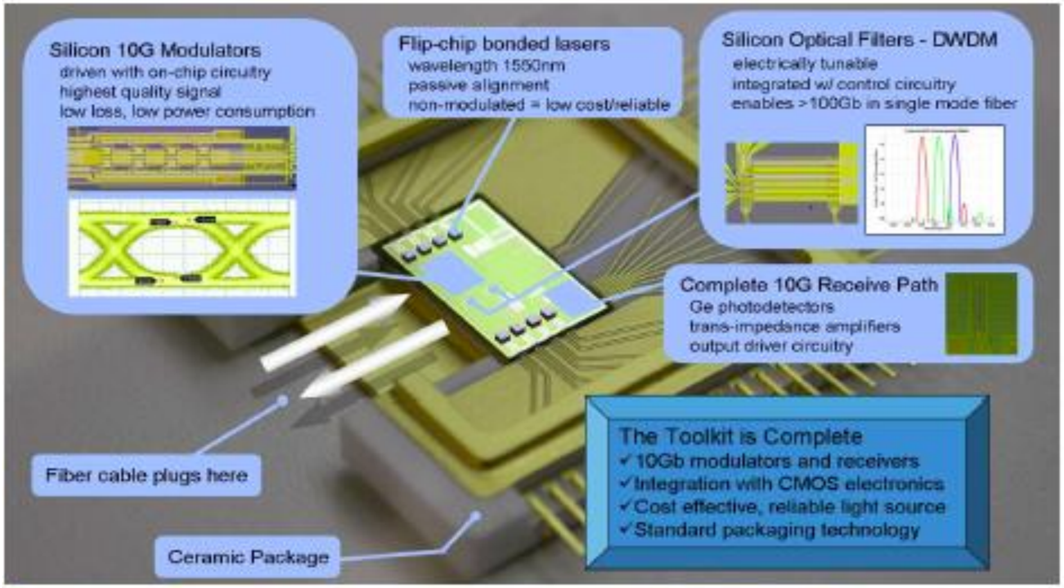


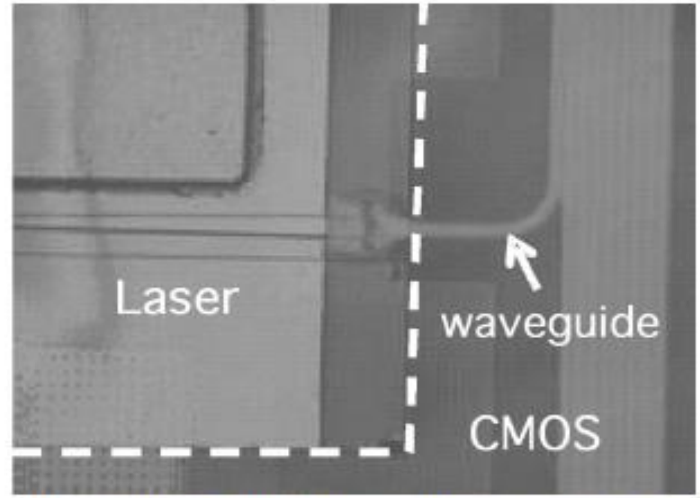


25G Transmit eye with low power drivers from **Oracle** (<70mW/ch)

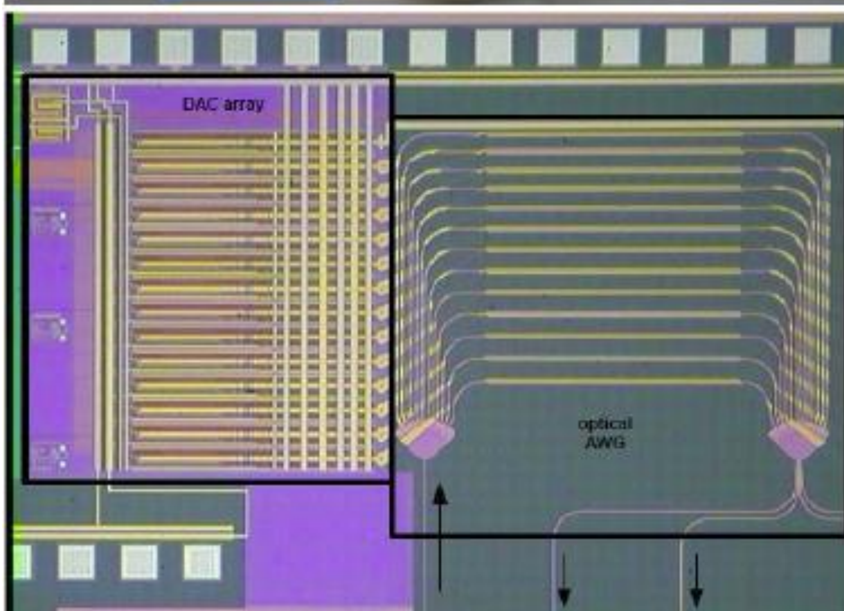
KOTURA

Luxtera's 4 x 10 Gb/s Si Transceivers

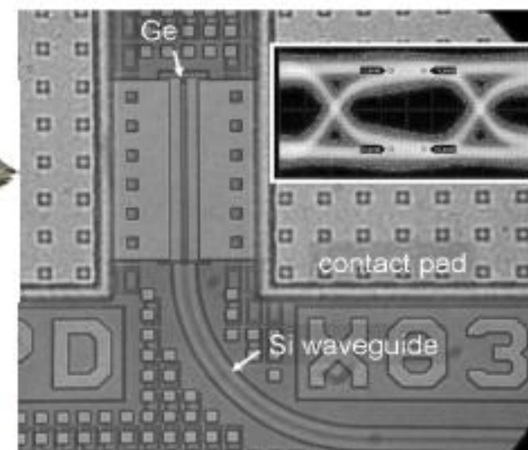




Top view of a flip-chipped laser on top of a CMOS die. The laser die is outlined by the dashed white lines.

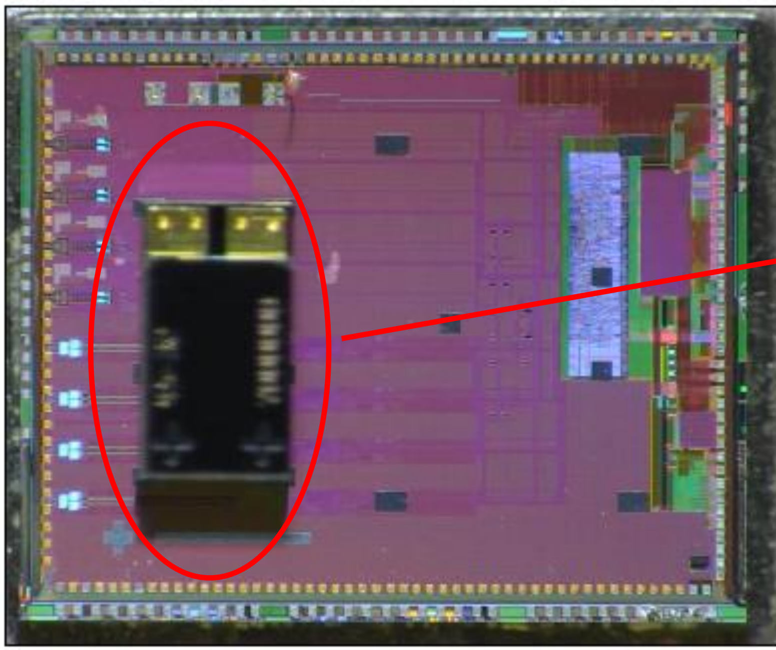


A. Huang *et al*., 2006 ISSCC



Germanium photodetector integrated into CMOS, shown with 10-Gbps eye

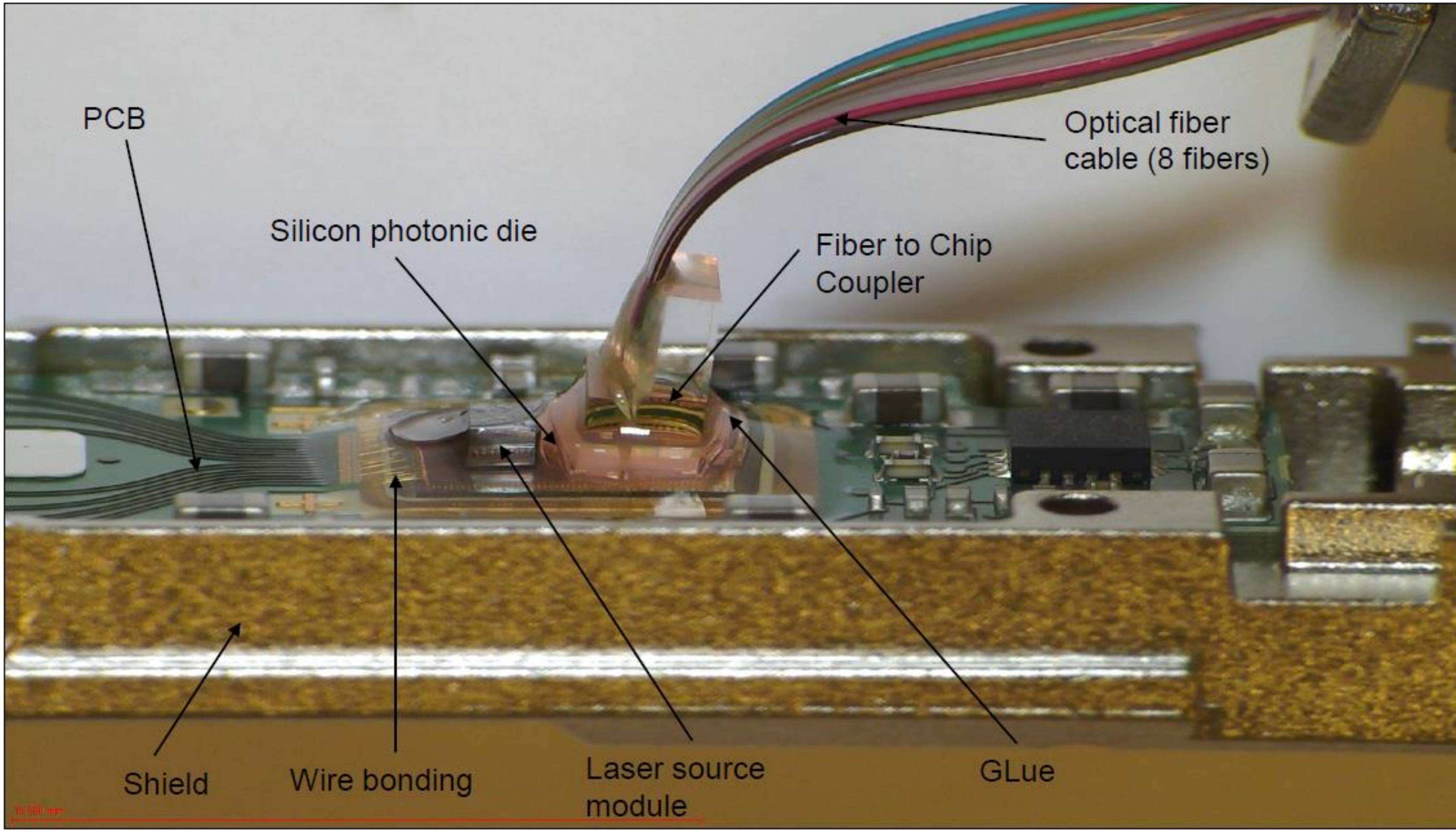
Molex’ AOC with Luxtera Si Photonic Die



Silicon Photonic die

MEMS Laser Source

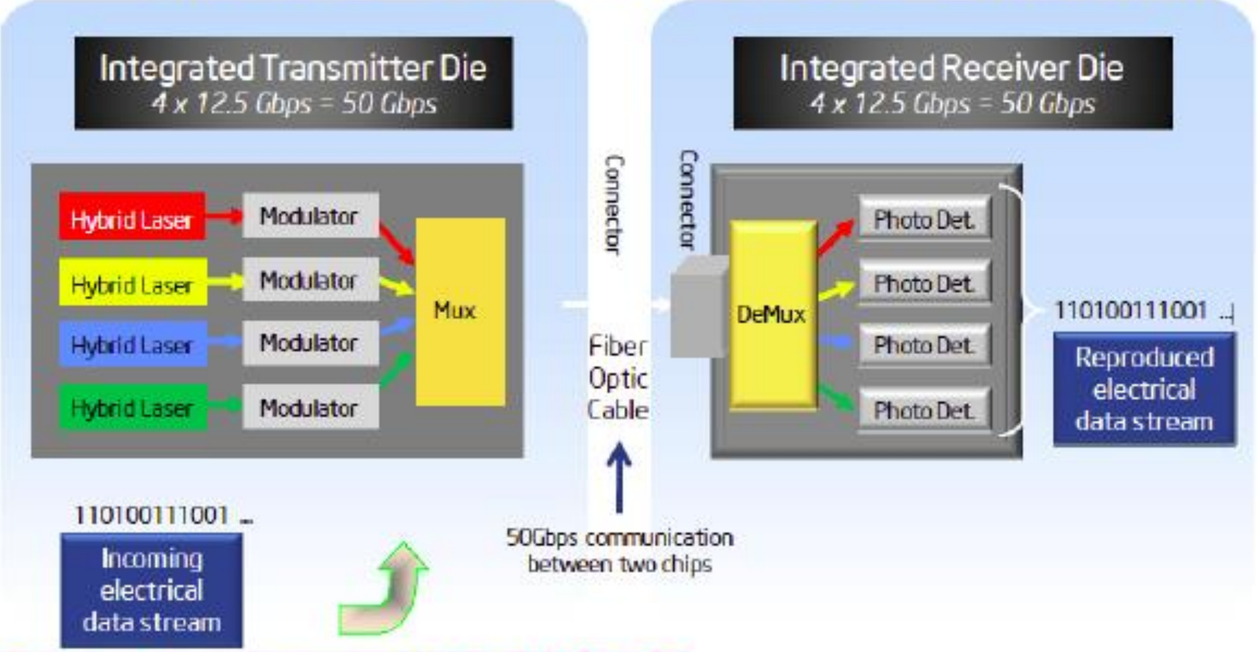
Fiber coupling



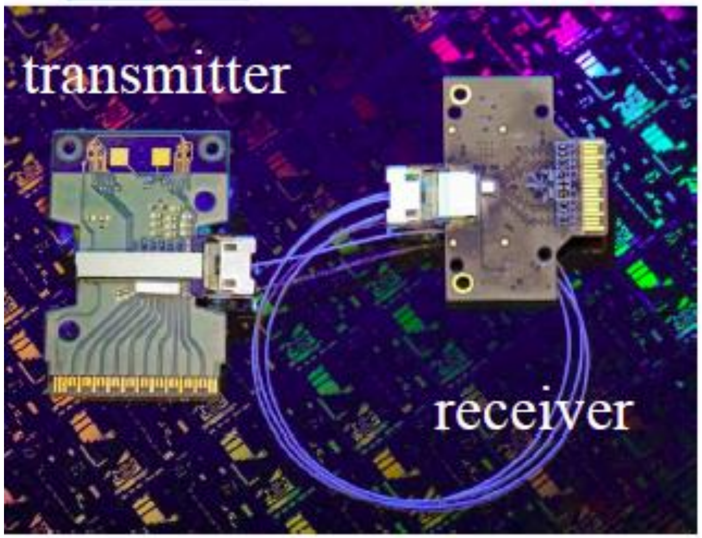
SYSTEMPlus CONSULTING

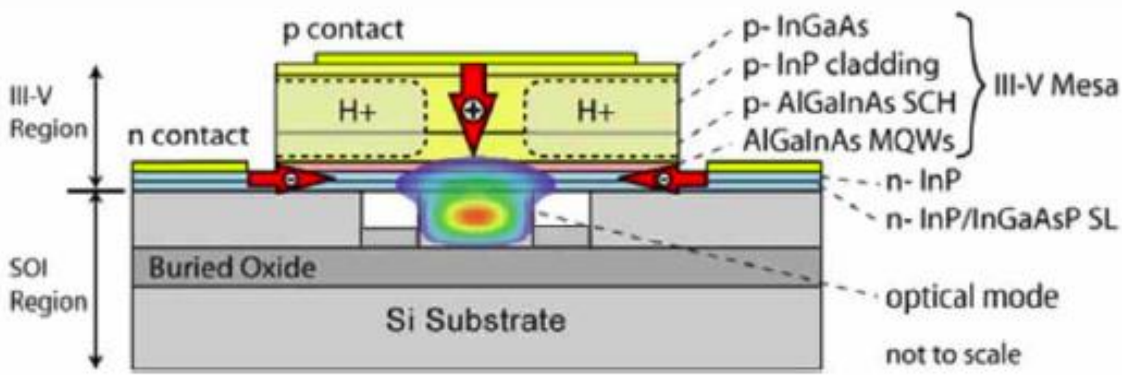
Optical fiber couplage – tilted view

Intel's 4 x 12.5 Gb/s Silicon Photonics Link



InP laser evanescently coupled into a Si WG





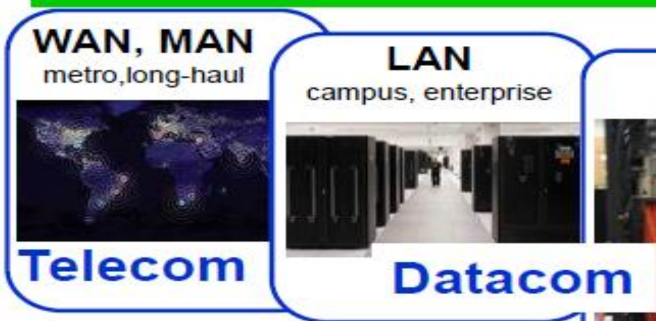
White Paper, Intel Labs, July 2010

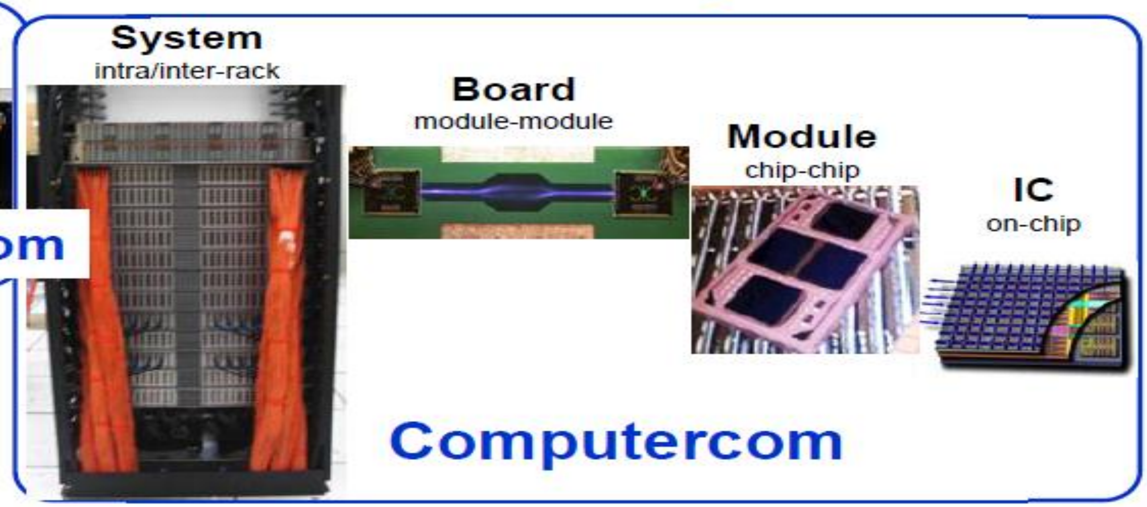
W. Fang *et al.*, Opt. Express **14**, 9203-9210 (2006)

Evolution of optical interconnect

Evolution of Optical interconnects

IBM



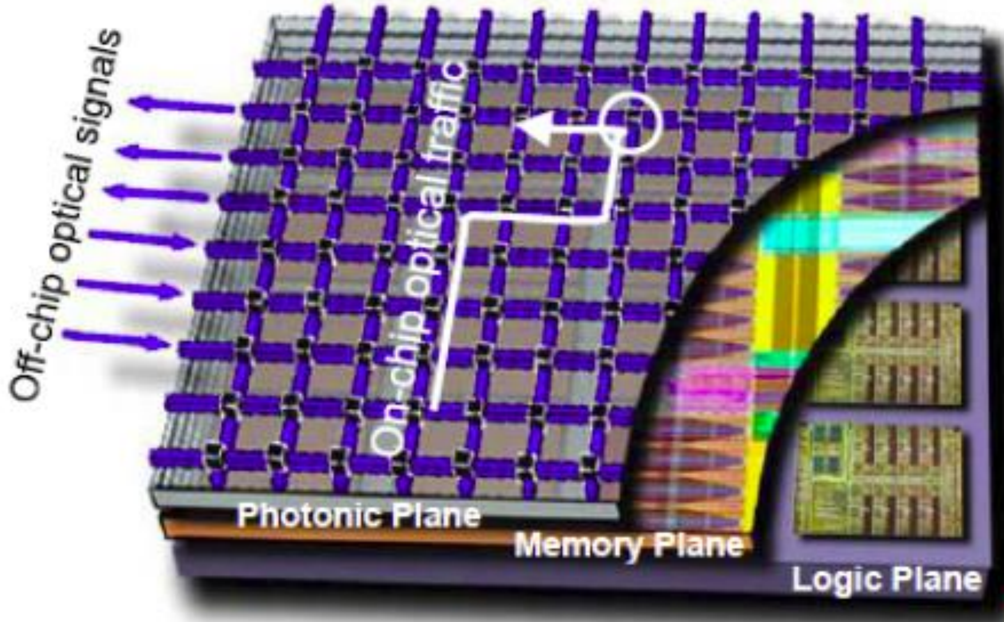


- BW*distance advantage of optics compared to copper leading to widespread deployment at ever-shorter distances
- As distances go down the number of links goes up putting pressure on power efficiency, density and cost

Increasing integration of Optics with
decreasing cost, decreasing power, increasing density

2020	1mW/Gb/s	$0.025/Gb/s

Vision for 2020 – Optically connected 3-D Supercomputer Chip



- 36 "Cell" 3-D chip
- Silicon photonics layer integrated with high performance logic and memory layers
- **Layers separately optimized for performance and yield**

Logic plane	~300 cores, ~5TF (36 "supercores")
Memory plane	~30GB eDRAM
Photonic plane	On-Chip Optical Network >20 Tbps (bidirectional) optical on-chip (between supercores) >20 Tbps optical off-chip

Photonic layer not only connects the multiple cores, but also routes the traffic

System level study:
IBM, Columbia, Cornell, UCSB

Courtesy of Jeff Kash

Summary

- ✓ Clear need/technology gap created by the explosive growth of Data/image communication

- ✓ Photonics /Silicon Photonics will be the platform of choice for interconnect resolving the major current technological issues: latency, bandwidth, power dissipation and signal integrity.

- ✓ A world wide ecosystem has developed over the last 10 years to generate the supply chain

- ✓ This is still a market in its infancy with challenges to be resolved: laser integration, low cost integration/ packaging/ standardization….