Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

SWISSLASER·NET

Evolving Gigabit to Terabit/s Interconnects –

a device point of view

Prof. Dr. Heinz Jäckel

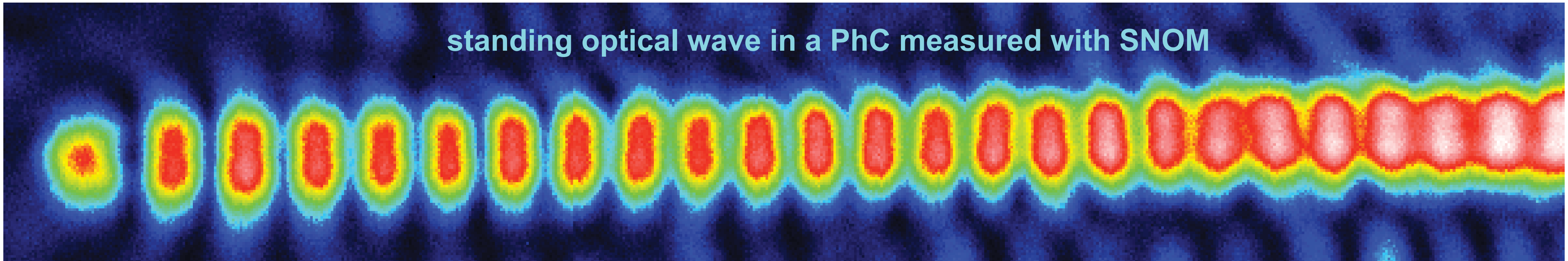
High Speed Electronics and Photonics Group
Electronics Laboratory, IfE
ETH Zürich, Switzerland

e-mail: jaeckel@ife.ee.ethz.ch,

www.ife.ee.ethz.ch

FIRST
Center for Micro- and Nanoscience

CASE Center for Advanced Silicon Electronics



Outline:

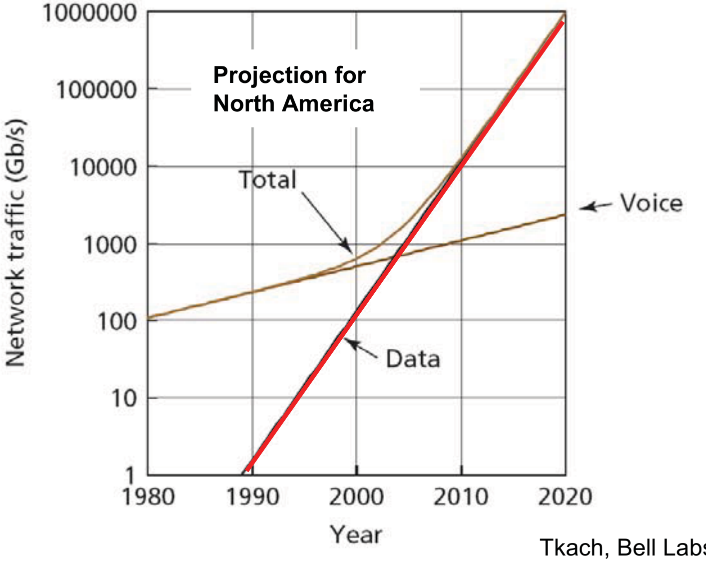
- *More Capacity and Speed: are Terab/s enough or do we need Petab/s ?*
- *Concepts / Status of Large Capacity ETDM, OTDM and OWDM systems*
- *Device Requirements of Tb/s Lightwave systems*
- *Towards +200 Gb/s Electronics*
- *Concepts and State-of-the-Art of Photonic Integration*
- *Device Examples for InP-based Monolithic Photonic Integration*
  - ***Sub-ps Monolithic Integrated Mode Locked Laser Diode (MLLD)***
  - ***Compact Semiconductor based sub-ps All-optical Switch (AOS)***
  - ***Photonic Crystals (PhC) for monolithic nano-scale downsizing of OICs***
- *Outlook: what next ?*

All our devices have been fabricated in the clean room facility of ETHZ

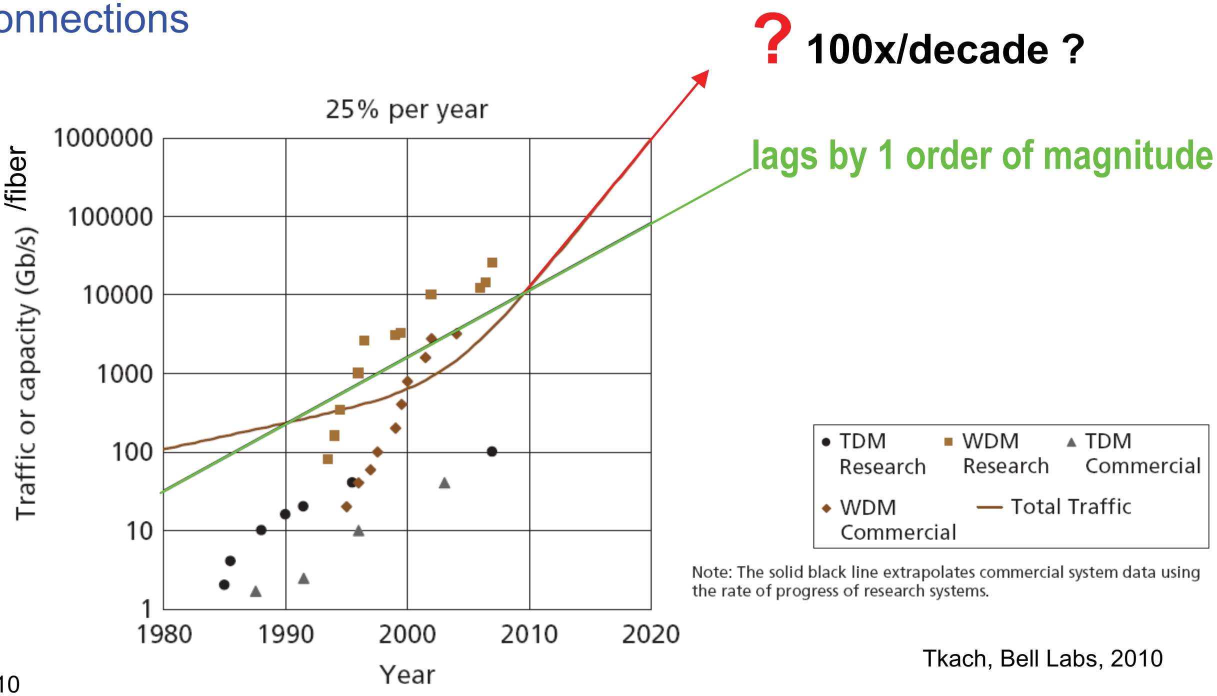
FIRST
Center for Micro- and Nanoscience

Do we have a communication bottle neck ?

- **What drives communication capacities and data rates?**
  - fast growing Internet communication
  - optical backbones for wireless
  - data-heavy services: video-on-demand, high quality pictures,
  - massive parallel computer system interconnections



Tkach, Bell Labs, 2010

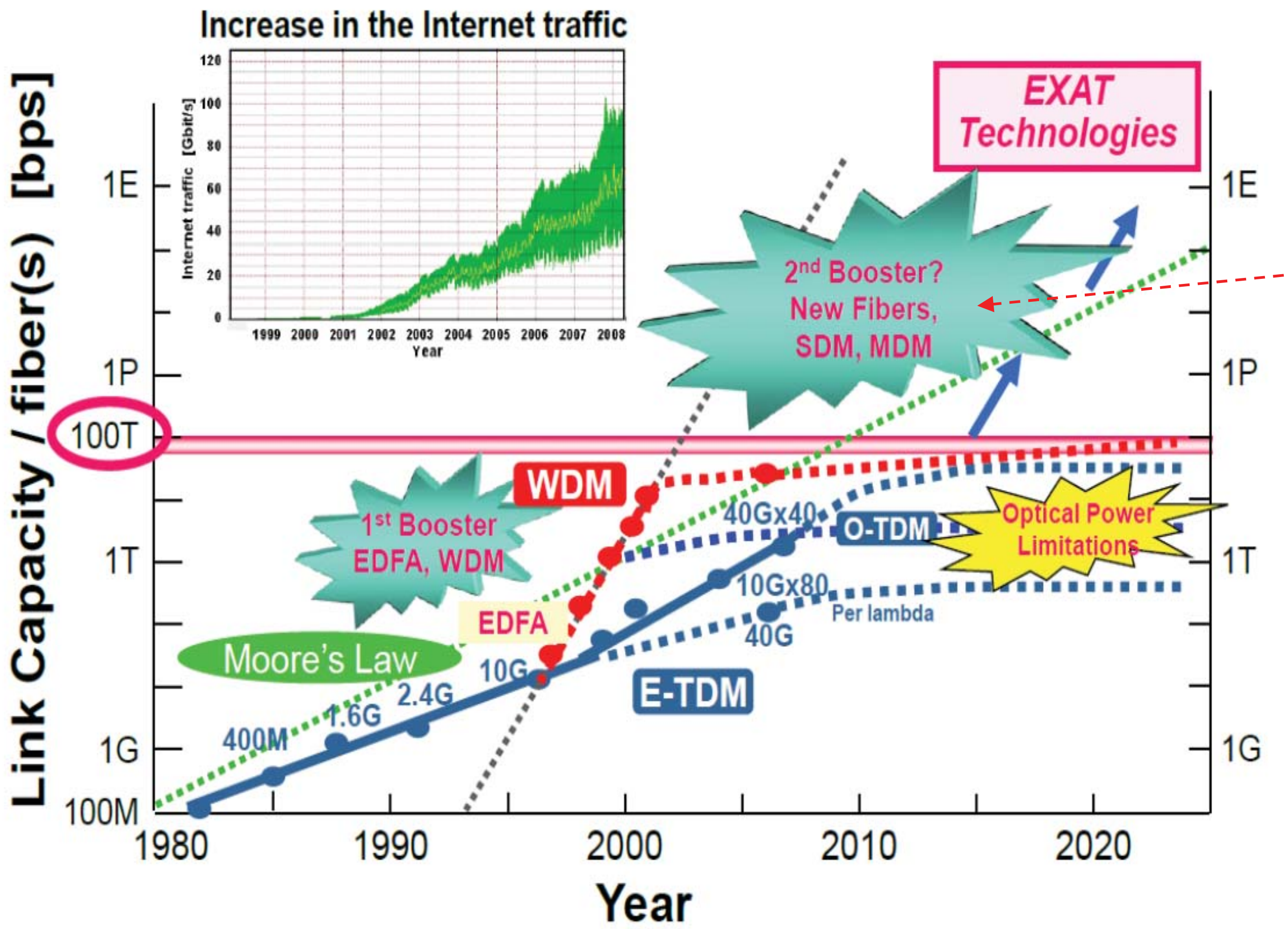


Tkach, Bell Labs, 2010

Major Challenges:

- After the “2001 bubble-bust”: substantial communication capacity bottle-neck for the emerging data com
- Implementation of novel concepts for 10-100x capacity and spectral efficiencies enhancement
- Massive optoelectronic integrations is underdeveloped but strategic for large-scale communication system
- Energy efficiency: Communication systems consume 2 – 4% of the electrical energy production !

Current Status and Projections of Lightwave Systems



Multi-level coherent transmission
Multicore fiber
Multimode control

Optical Integration ???

Nakazawa, Tohoku Uni, 2010

- **ETDM** (electrical time division multiplex) gated by electronic data rates (40 Gb/s ➡100 Gb/s ➡ 250 Gb/s ?) and optical modulator bandwidth demonstrated 100 Gb/s.
- **OWDM** (optical wavelength division multiplexing) has demonstrated 35 Tb/s (69Tb/s, 2010)
- **OTDM** (optical wavelength division multiplexing) stagnating at 1.2 – 5 Tb/s (2010)

Multiplexing Concepts of Tb/s Lightwave Systems

- **Optical fiber as ideal transmission medium**

  + ~ 60 THz optical bandwith @ ~210 THz carrier

  ➡ ***~60 Tb/s Capacity/fiber ($\Delta\lambda$=400nm)***

  + low loss ~ 0.2 - 0.5dB/km (optical amplification for long distance)

  + low dispersion ~5ps/nm/km (dispersion compensation for long distance)

  + small cross-section

  + nonlinear effects with fs time constants (ultrafast optical gates)

Wavelength bands: 180 – 240 THz

Band	Description	Wavelength range
O band	original	1260–1360 nm
E band	extended	1360–1460 nm
S band	short wavelengths	1460–1530 nm
C band	conventional ("erbium window")	1530–1565 nm
L band	long wavelengths	1565–1625 nm
U band	ultralong wavelengths	1625–1675 nm

- fibers are nonlinear at high signal power (- optical crosstalk, power limit)
- random polarization dispersion effects
- heritage of millions of installed "standard" fiber-km !

• Tb/s Signal Multi-/Demultiplexing in the Optical Domain

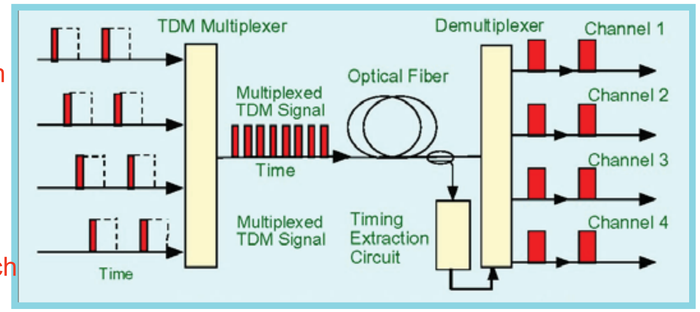
Transmission of modulated, time-interleaved sub-ps –pulses at t_1 - t_N ➡ OTDM (ps pulses, DEMUX ps-gates)

Transmission of modulated optical carrier waves λ_1 - λ_N ➡ OWDM (sub-nm wavelength control of sources, DMUX)

OTMUX **OTDM:** OTDMUX

1) λ_0, t_1, B_{ch}

N) λ_0, t_N, B_{ch}

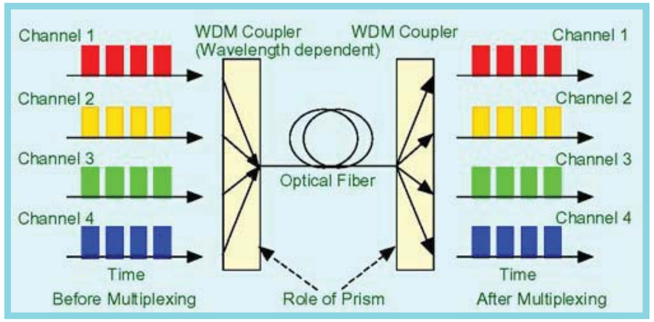


λ_0 , B_{tot}=NB_{ch}

OWMUX **OWDM:** OWDMUX

1) λ_1, B_{ch}

N) λ_N, B_{ch}



λ_1 –λ_N, B_{tot}=NB_{ch}

Generic Lightwave Systems

• *Electronic Time Division Multiplex ETDM* (single wavelength)

Channel-MUX, DMUX and Clock/Data Recovery (CDR) in the Electrical Time Domain

➡ Total Channel rate B_{tot}=N B_{ch} limited by the electronic “bottle neck” (40Gb/s, → 160 Gb/s, +200 Gb/s ?)

➡ Optical components (Diode Lasers, fast EO-modulators, fast Photodetector) operate @ B_{tot}

Electronic data rate relaxed by multi-level or coherent multi-symbol/bit modulation (OOK ➡ PSK, DQPSK)

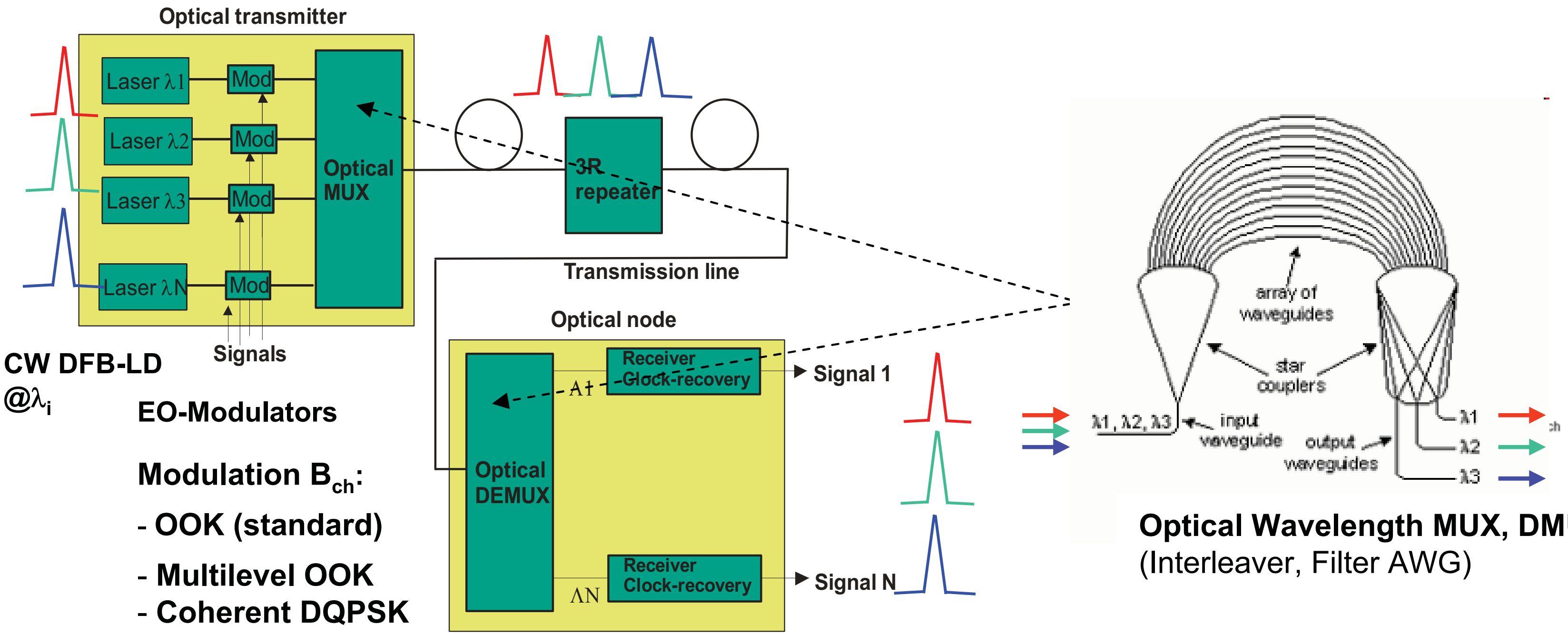
• *Optical Wavelength Division Multiplex OWDM*

Channel-OWMUX, ODWMUX in the Optical-Domain, Clock/Data Recovery (DCR) in the Electrical Domain

➡ OWMUX, OWDMUX and laser sources limit B_{tot} by wavelength λ_i, opt. bandwidth $\Delta\lambda_i > \lambda_i^2/cB_{ch}$ and spectral efficiency control → **wavelength critical ($\Delta\lambda$<<0.2nm ~ 100GHz, ~10^{-4})**

High channel rate B_{ch} simplify OWDM complexity, trade-off: high device count of OWDM ⬅➡ simple electronics

Major drivers: Tb/s Long haul, LAN, etc. Photonic Nets, 100GbEthernet, Computer Interconnects, etc.

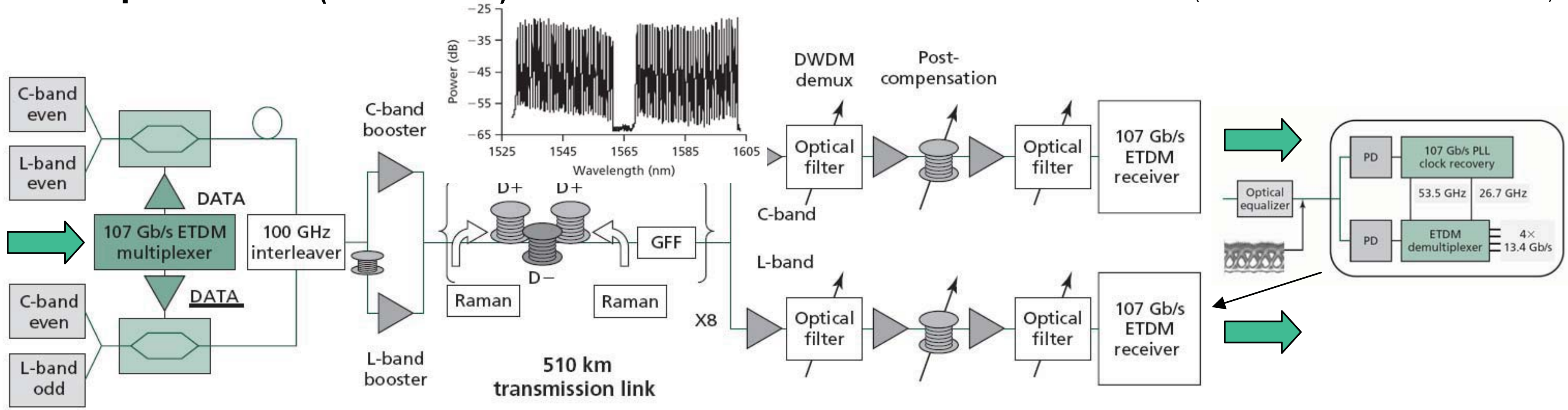


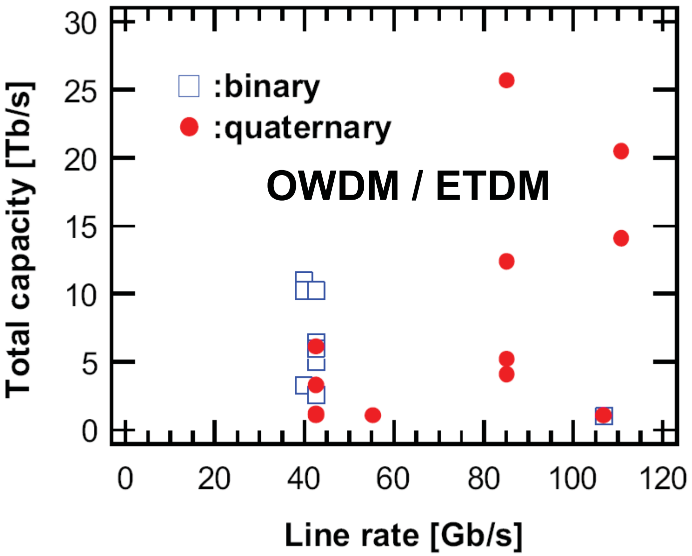
Optical Wavelength MUX, DMUX
(Interleaver, Filter AWG)

State-of-the-Art Lightwave Systems

- *Multi-10Tb/s Optical Wavelength Division Multiplex OWDM*

Example: "8Tb/s (80x107 Gb/s) DWDM NRZ-VSB over 500km NZDSF" (K. Schuh et al, 2009 Alcatel-Lucent)





32 Tb/s (320x114Tb/s) over 500 km (X. Zhou, 2010)

69.1 Tb/s (432x171Tb/s) over 240 km (A.Sano, 2010)

Requirements, Challenges and Limitations:

- **Ultrafast InP-HBTs/HEMTs, SiGe-HBTs Electronics 40 → +160 Gb/s critical** ✓
- EO-Modulators with <u>low</u> drive voltage, LiNb-MZI, EAM marginal (✓ ?)
- DBR-LD-EAM (integrated) 40 → +100 Gb/s (✓ ?)
- side illuminated PD → 300 Gb/s possible ✓

OWDM:

- **AWG-MUX, DMUX, DBRLD are λ-critical, sub-nm filtering:** $\delta\lambda << \lambda i^2/cB_{ch} = \lambda_i^2/cB_{tot}/N$ ✓
- broadband optical amplifiers, total power limitation critical (✓?)
- dispersion management moderate ✓
- high device count requires integration ! (- ?)

Generic Lightwave Systems

- *TB/s Optical Time Division Multiplex OTDM*

Channel-OTMUX, OTDMUX and Clock Recovery (CR) in the Optical Time Domain (sub-ps bit slots $\Delta t @ \lambda_0$)

➡ sub-ps optical pulse sources with repetition rate of the channel rate B_{ch} required (mode-locked lasers)

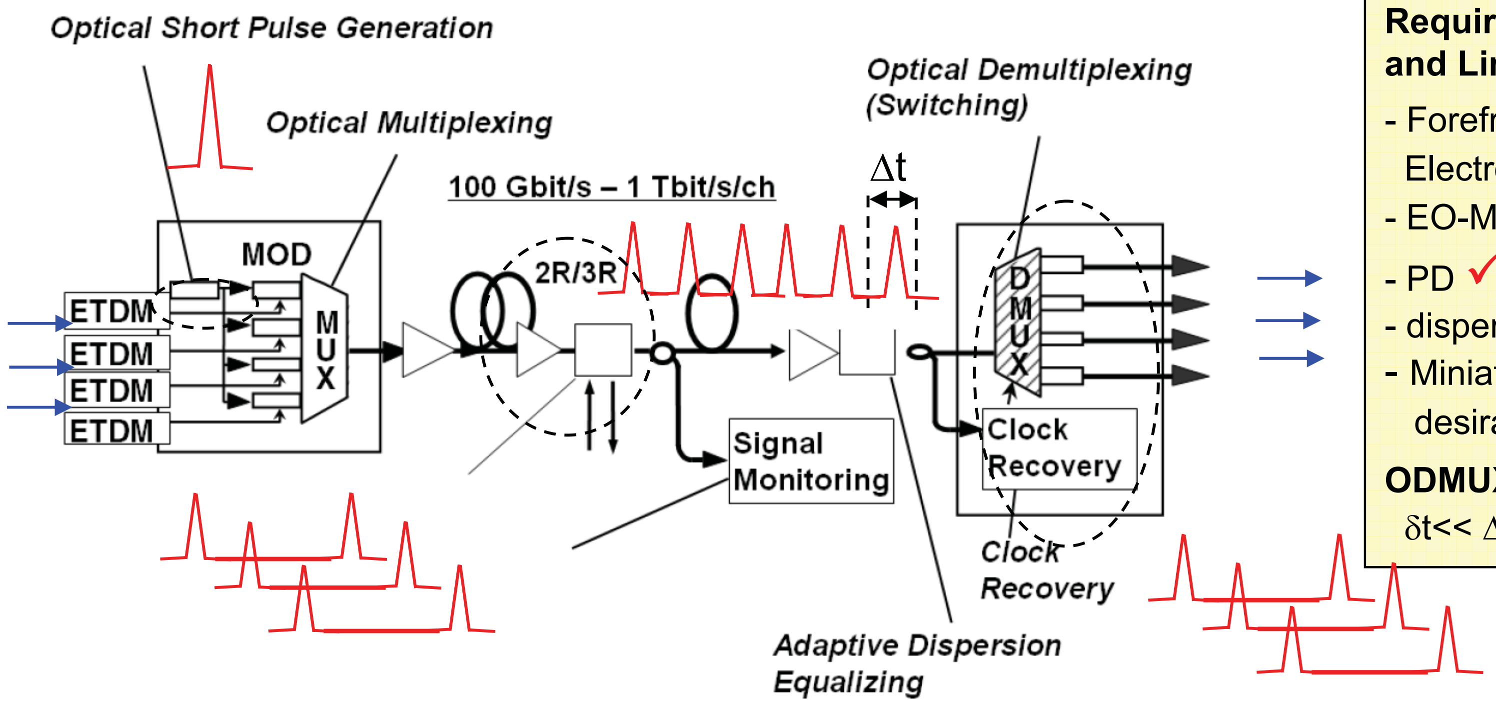
➡ Ultrafast OTDMUX (gate) and OCDR operate at the aggregated optical Tb/s data rate B_{tot} with sub-ps switching times ➡ all-optical switches and nonlinearities required ➡ **time critical ($\Delta t << 1/B_{tot}$ ~ 100fs !)**

➡ Optoelectronic devices (Mode-locked Laser, EO-modulators, Photodetector) operate at the electrical channel rate B_{ch}

Only one optical pulse source and one wavelength required → moderate device count of OTDM (~$1/B_{ch}$)

Major drivers: Tb/s long haul, high capacity Data-Highways, transparent All-optical Routers (future)

Concept of OTDM:



Requirements, Challenges and Limitations:

- Forefront InP-HBTs/HEMT, SiGe-HBT Electronics ✓
- EO-Modulators with low drive voltage (✓)
- PD ✓
- dispersion management critical (✓)
- Miniaturization to SC-OTDMUX, MLL desirable (- ?)

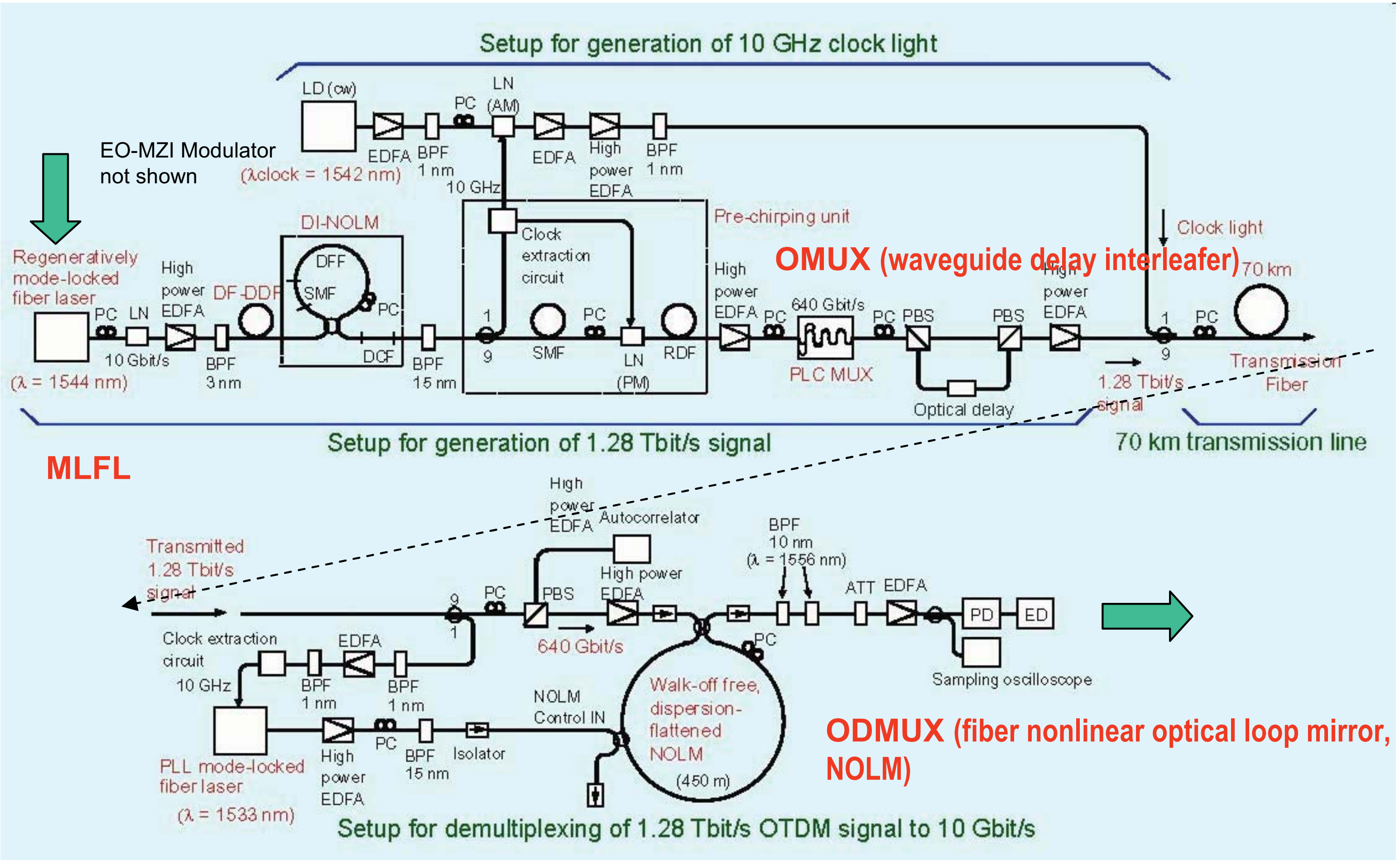
ODMUX, MLL, 3R are time-critical:

$\delta t << \Delta t = 1/(NB_{ch}) = 1/B_{tot}$

State-of-the-Art Lightwave Systems

- *TB/s Optical Time Division Multiplex OTDM*

Example: Research State-of-the-Art (fiber based)
"1.28Tb/s – 70km OTDM with fourth-order dispersion compensation" (M. Nakazawa et. Al, 2000, NTT)



Hero-Experiments:

2.56Tb/s over 160km
(Weber, HHI 2006)

5.1Tb/s
(Hansen Mulvad, Uni Denmark 2010)

OTDM is about 10x slower than OWDM

All components are fiber-based and large

➡ **Miniaturization and Integration: need for stronger nonlinear effects in semiconductors DEMUX, CD**

Toward aggregated Tb/s data rates in Computer Links

CMOS Roadmap (ITRS) for short distance, parallel Tb/s Optical Interconnects:

Year of production	2006	2008	2010	2012
gate length	48nm	38	30	24
Supply voltage	1.1 V	1.0	1.0	0.9
On-chip clock	6.8 GHz	10.9	15	20
Transistor count	550 M	1100	2200	2200
I/O Count per Chip	2100	2200	2400	2500
Max Chip Power (10W per.)	180 W	200	200	200
Serial Data Rate	6 Gb/s	10	14	18
Channel Number	200	200	200	200
Aggregated Date Rate	1.2 Tb/s	2.0	2.8	3.6
Max Power/Transceiver	8.2 mW /Gb/s	5.5	4.3	3.3

Electrical I/O-Bottle Neck for Computers/Servers:

- box-to-box
- board-to-board
- processor-to-processor
- on-chip ?

} 10m – 1cm

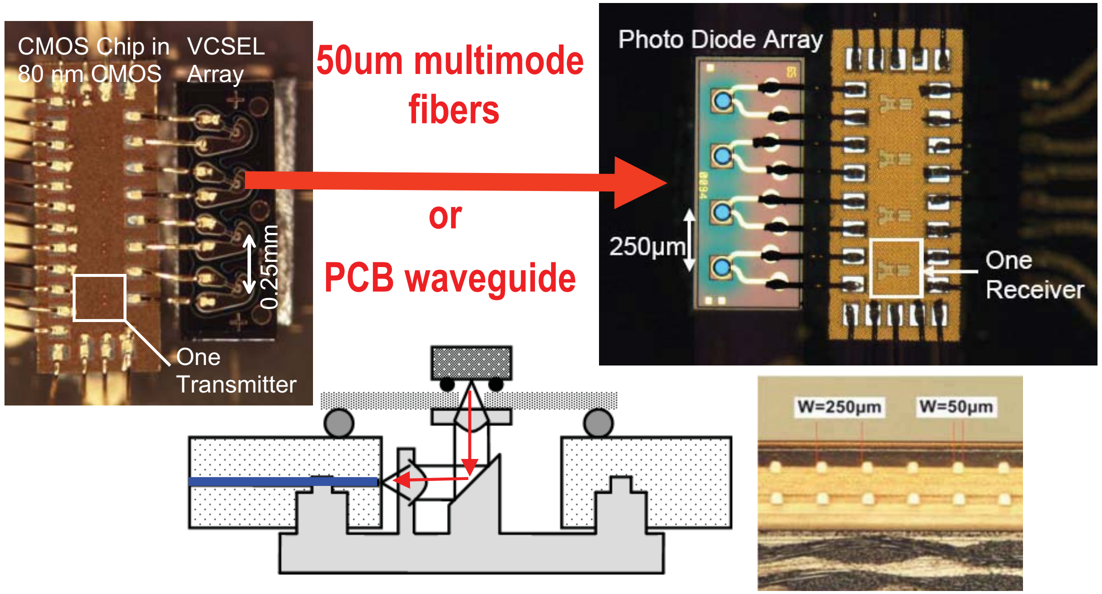
4x10 Gb/s CMOS-VCSEL interconnect @2.5mW/Gb/s
(Kromer et al., IfE, ETHZ)

High performance optical interconnects
benefit from optical / optoelectronic integration

➡ **low power** (<10mW/Gb/s) **for for high I/O count**

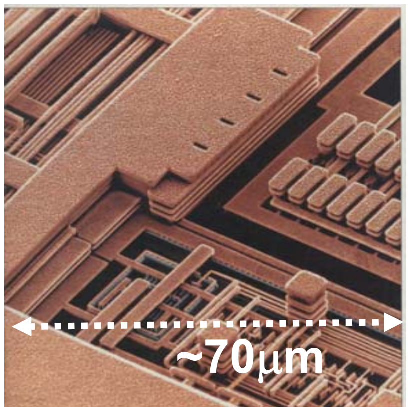
➡ **integrated dense optical "wiring" through the whole packaging hierarchy**

➡ **scalability and cost effectiveness**



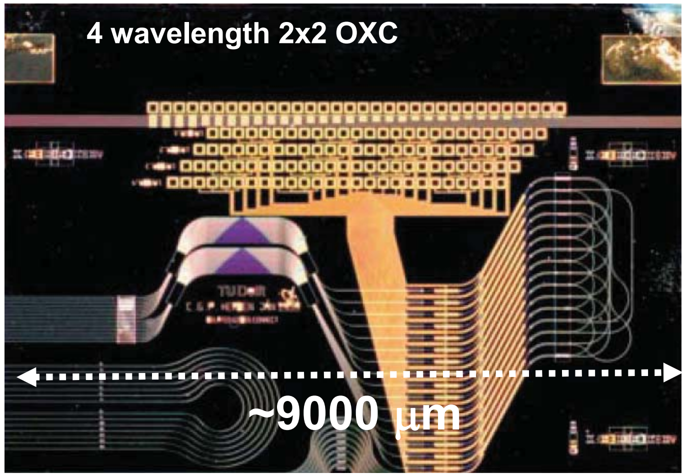
Device Requirements for Tb/s Lightwave Com

- **Fast Analog and Digital Electronics for RX/TX and ETDM front ends** (+40 - +200 Gb/s): ☒
  - +150 Gb/s demonstrated with HBTs, +250Gb/s projected
  - Integration with Optoelectronics very difficult, few demonstrators (mostly PD+Amp) marginal
- **Fast Active Optoelectronic Devices** (+40Gb/s):
  current modulated LDs ~40GHz marginal, EO-MZI/EA-modulators ~40–100GHz, photodetectors ~40–300GHz
- **Compact Passive Optical Components:**
  λ-MUX/DMUX, couplers, isolators, dispersion compensators, λ-converters, … @ higher / denser functionality ?
- **Ultra broad band optical amplifiers**
- **Cost-effective packaging with low insertion-loss, high bandwidth and I/O count**
- **Integrated Waveguide / Free-Space Technology on board-, module- and chip-level**
- **Ultra-fast All-Optical Devices for multi-100 Gb/s for OTDM:** ☒
  Compact sub-ps pulse sources, all-optical switches, 3R (transition from fibers to semiconductors) marginal
- **Optoelectronic Integration and Miniaturization:** ☒



$1:10^4$ in area density
(wiring limited, waveguide bend radius)

marginal

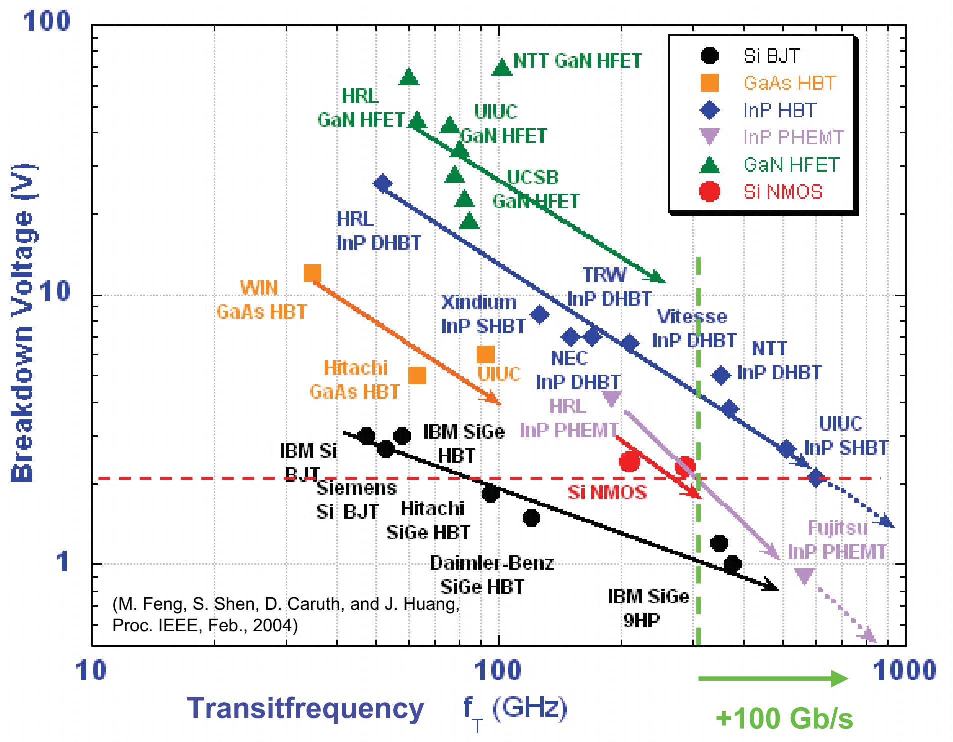


Progress towards +200 Gb/s Electronics for ETDM

- **Higher channel data rates in ETDM simplify OTDM or OWDM system complexity**
- **Improve bandwidth efficiency (bit/Hz)**

Scaling Electronics to +200 Gb/s

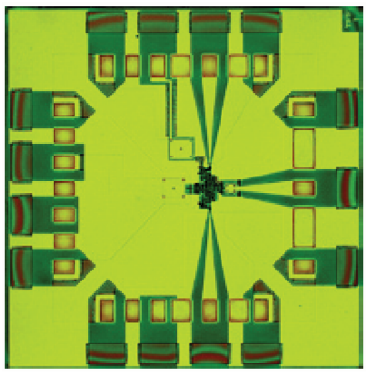
- **lateral / vertical device nano-scaling,**
- **keeping acceptable signal voltages**
- **new materials for band engineering, high carrier velocity and breakdown**
- **ultimate reduction of device / wiring parasitics**



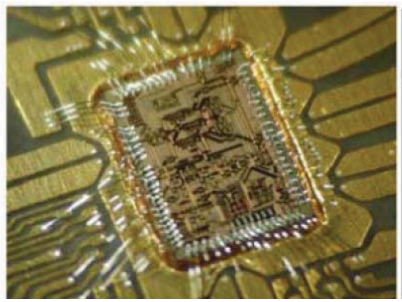
InP- / SiGe-HBT Speed Performance:

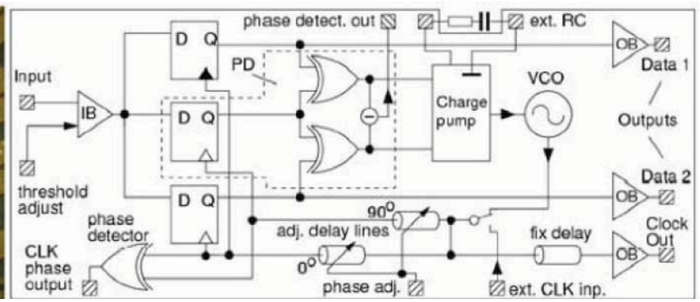
Function	Technology	Speed (Gb/s)	Year
Mux4:1	SiGe 0.13 μm	132	2004
Mux2:1	SiGe	100	2007
Mux4:1	InP DHBT	165	2005
Mux4:1	InP HEMT	144	2004
Mux2:1	InP HBT	120	2004
Demux1:2	InP HBT	100+	2007
Demux	InP HEMT	100	2004
Demux	InP HBT	110	2004
Demux1:4	InP DHBT	100	2006
CDR and Demux1:2	InP DHBT	100	2008
CDR and Demux1:2	SiGe	100	2008
Driver	InP HEMT	110+	2003
Driver	InP DHBT	80+	2006
Driver	InP DHBT	100+	2008

150 Gb/s ½ Frequency Divider
InP HBT-IC NTT, 2004



100 Gb/s Demultiplexer and Clock Recovery
SiGe HBT-IC Siemens, 2006





Scaling Projections with 2D hydrodynamic HBT Models

HBT-Model (Dessis® with Stratton's "Ansatz") **verified on 100 Gb/s InP/InGaAs HBTs includes:**

- 2-D geometry and heterojunctions
- non-stationary carrier transport equation (Stratton)
- bench-mark circuits (RO, FD, MUX) including external parasitics

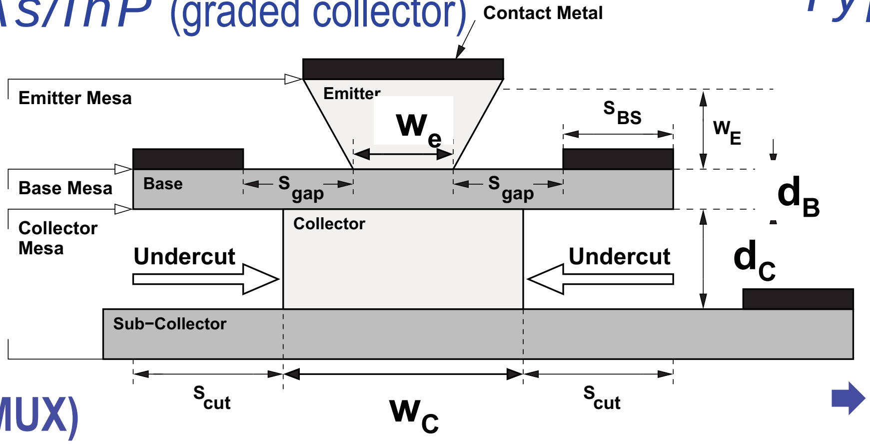
Type I: InP/InGaAs/InP (graded collector)

w_e = 200nm ; w_C=600nm ;

d_B=25nm ; d_C=100nm →

f_T = 570 GHz
f_{max} = 445 GHz
t_g = 1.77 ps

➡ *B = 215 Gb/s* **(RO, MUX)**



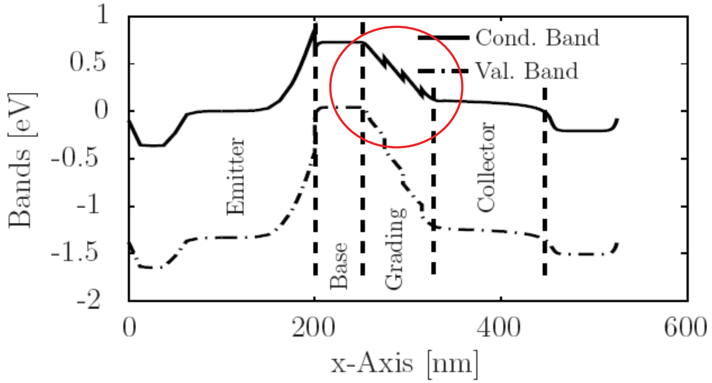
Type II: InP/GaAsSb/InP

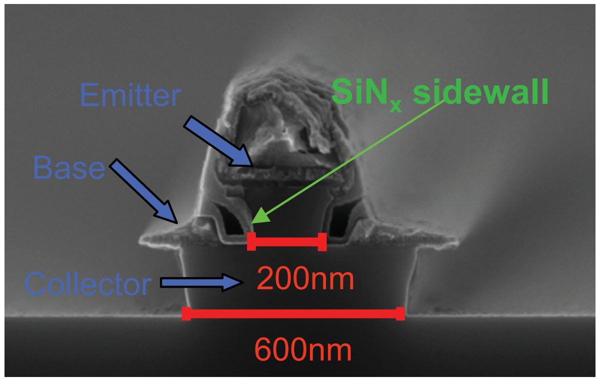
w_e = 200nm ; w_C=600nm ;

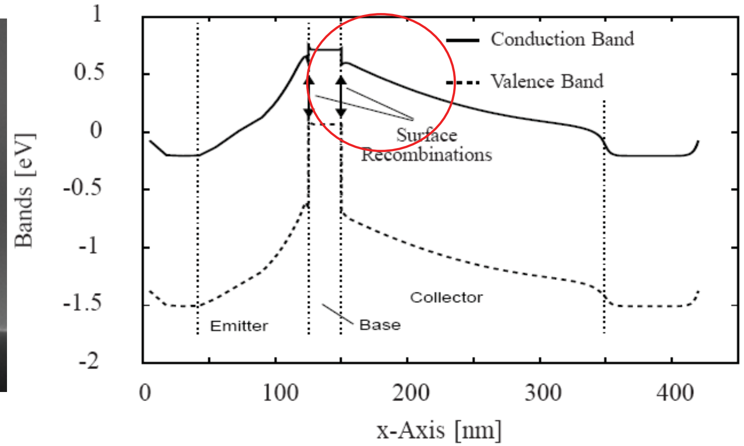
d_B=15nm ; d_C=100nm (50) →

f_T = 750 GHz
f_{max}= 600 GHz
t_g = 1.58 ps

➡ *B = 245 (300) Gb/s* **(RO, MUX)**





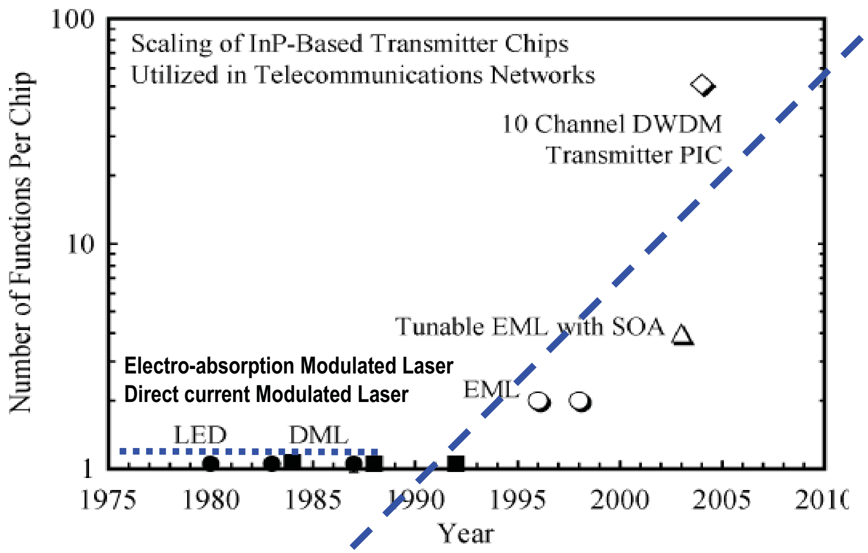


➡ *+250 Gb/s IC Operation for HBT is a realistic goal !*

Photonic Integration: a Technology Bottle-Neck

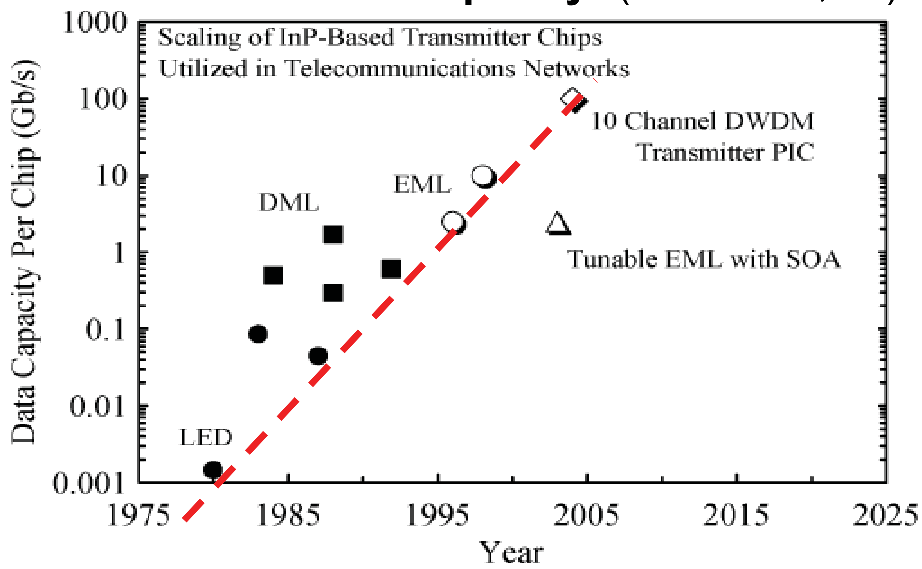
- **Photonic Integration (PI) reflect s not Moore's dynamic of Electronics (~1DK/3y) and Networks**
- **Internet and Moore's dynamic will only be met by PI**
- **PI must promote** *bandwidth, functionality, density, scalability and cost*

Functional Density: (InP-based, Tx)



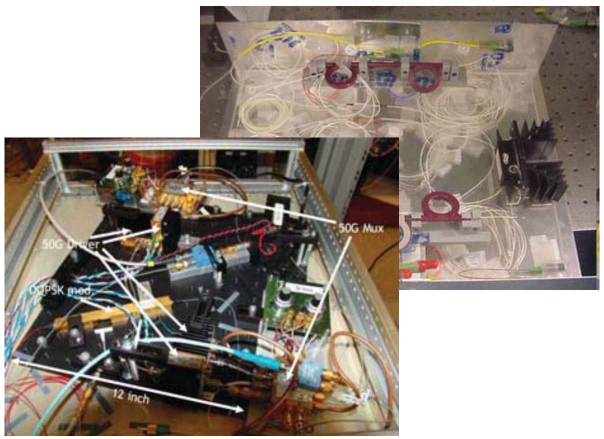
1 DK/15y

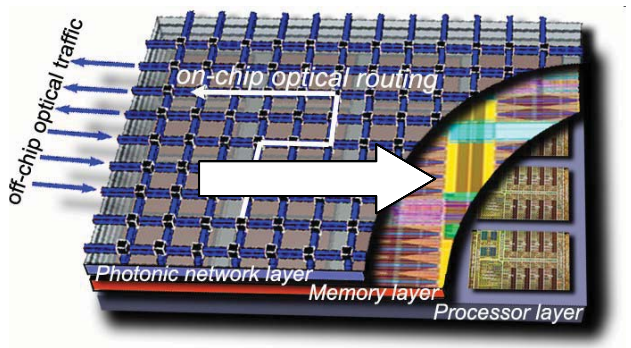
Bandwidth Capacity: (InP-based, Tx)

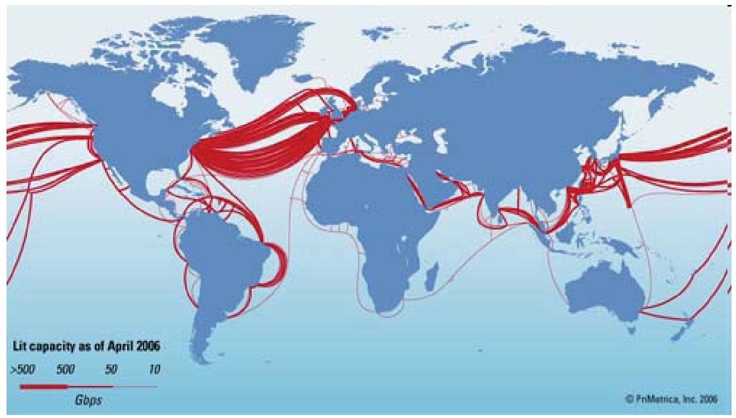


1 DK/5y "Moore-like" growth

Courtesy: R. Nagaranjan, 2005
Infinera





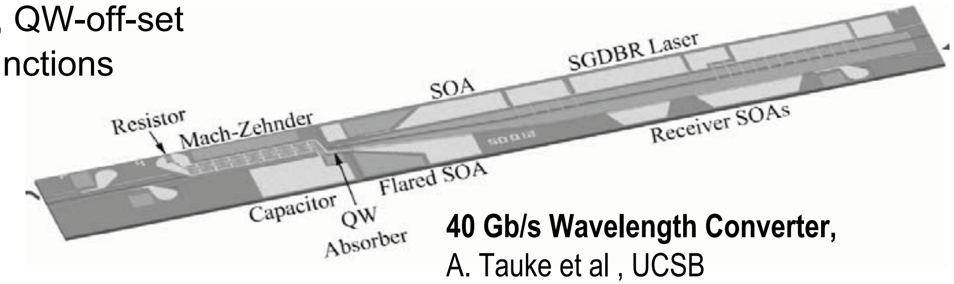


State-of-the-art of photonic SSI - MSI-Integration

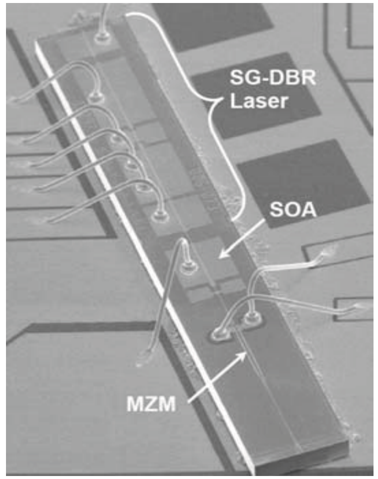
1) **λ-tuneable laser diode with modulator / amplifier / λ-converters**

(R&D, commercial)

integration technique: regrowth, QWI, QW-off-set
SSI- integration level: 2 - ~6 device functions
array capability



40 Gb/s Wavelength Converter, A. Tauke et al , UCSB

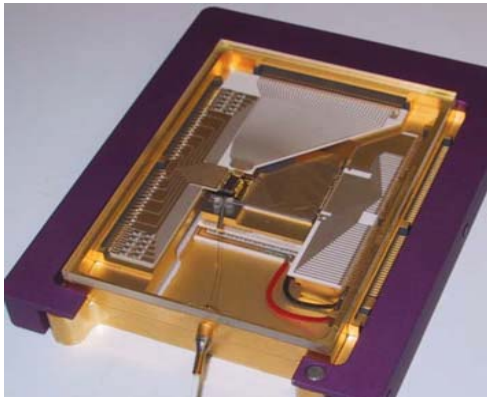


Transmitter IC , UCSB

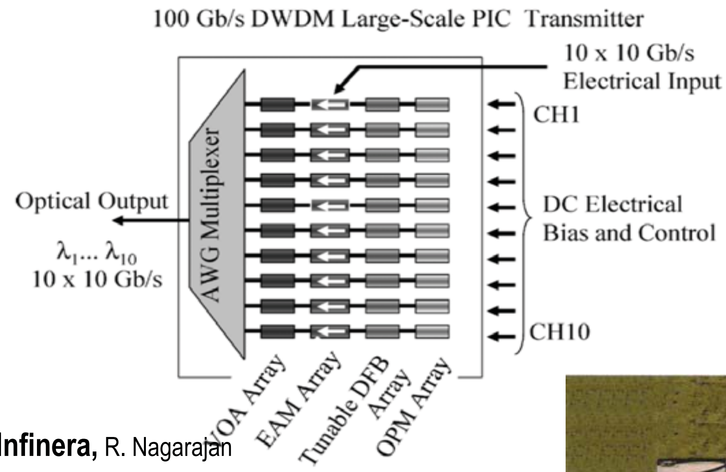
2) **Array Waveguides (AWG), LD, Modulators and SOAs**

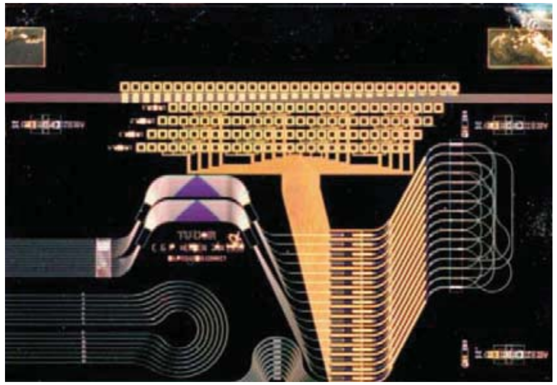
(R&D, commercial)

integration technique: regrowth
MSI-integration level: 100 – 200 device functions



400Gb/s (10x40 Gb/s) Tx, Infinera, R. Nagarajan



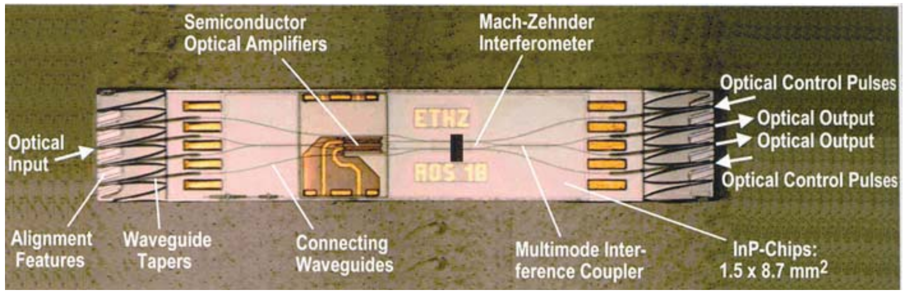


WDM XC, COBRA, M. Smit TU Eindhoven

3) *InP All-Optical SOA MZI-switches*

(R&D)

integration technique: regrowth, QWI, …



SOA-MZI-AOS with 500fs switching time (~500 Gb/s), R.Schreieck, H. Melchior, ETHZ

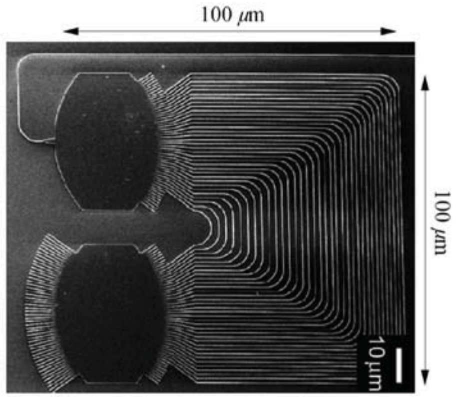
State-of-the-art of photonic MSI-Integration

4) *Monolithically integrated MLLDs*
(R&D, commercial @ 2-3 pulse width)
integration technique: regrowth, SAG, ….

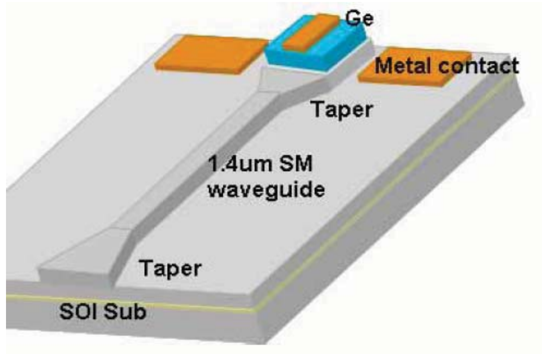
5) **Silicon Photonics**
(R&D)
integration technique: SOI, SiGe, MOS
integration level: 2 - ~few device functions

6) **III-V on Silicon Photonics**
(R&D)
integration technique: Hetero-Epitaxy and Waver-Bonding

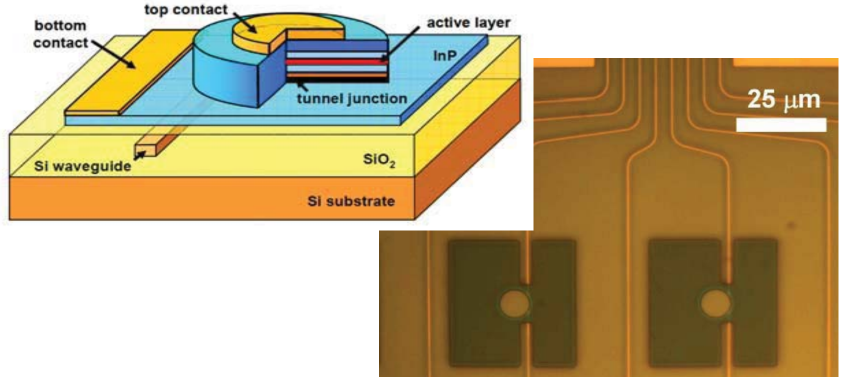
7) **Electronics and Photonics**
(R&D, commercial)
integration technique: regrowth / combined
integration level: mainly PD + amplifier chain



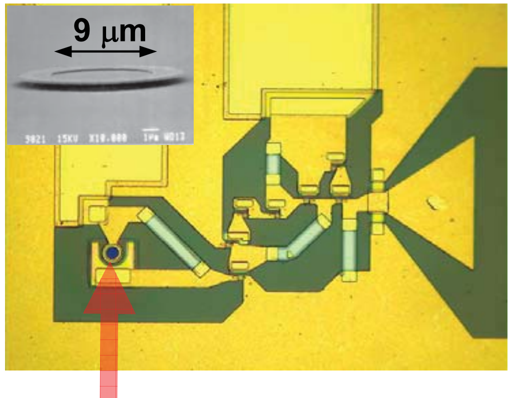
SOI AWG, T. Fukazawa et al, Yokohama Uni



31 GHz Ge nip PD on SOI, T. Yin et al, Intel

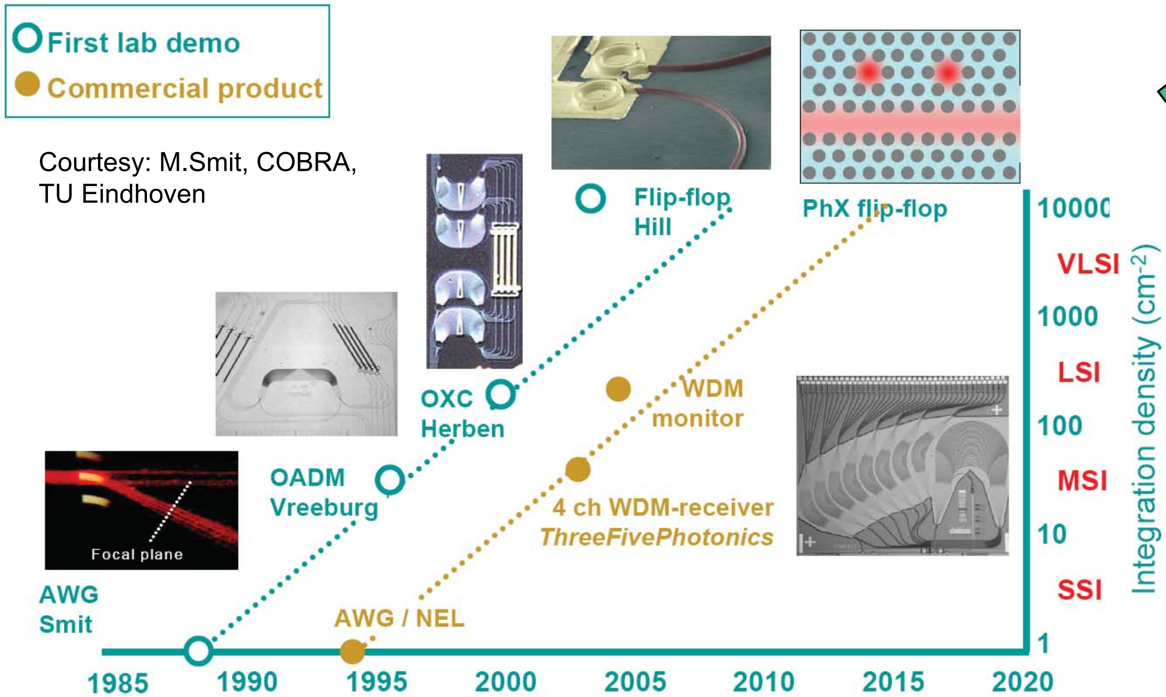


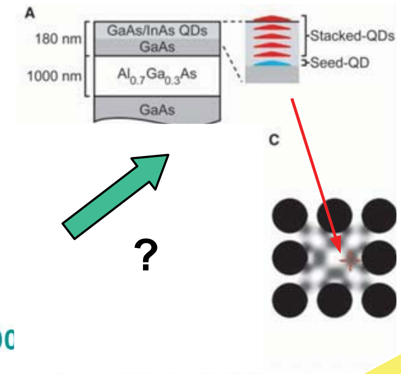
InP-Microdisk lasers on SOI Substrate, J. Van Camphouten, IMEC



70 Gb/s InP-HBT-Photoreceiver, D. Huber, IfE ETHZ

Progress in monolithic photonic integration





Quantum-Photonic Devices

- **Nano-Photonics** (Quantum dots)
- **Plasmonics**
- **Photonic Crystals** (bandgap WG)
- **Photon Wire Circuits** (high contrast WG)
- Micro-Photonics (low contrast WG)

increasing optical and electronic confinement

➡ **λ-scale device dimensions and interconnection by:**

Major Inhibitors of PI:
- **Technological barriers and heterogeneity of photonic devices**
- **Lack of high volume applications**
- **Foundry culture and technology platform** $\rightarrow$ **lack of economy of scale**

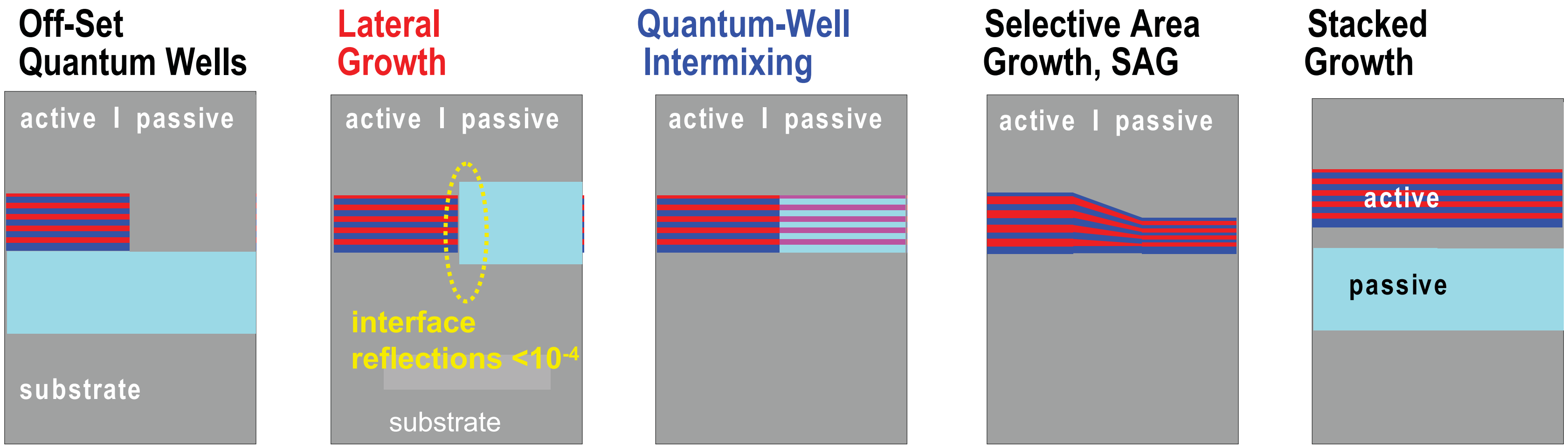
Technology Concepts for Optical Monolithic Integration

Passive: 2D-WG, gratings and mirrors (Fiber-WG junction, bend, splitter, coupler, resonator, isolator (?), ...)

Active: SOAs, LASERs, photodetectors, modulators, switches, ...

Integration goal: local control of bandgap E_g, doping n, p, vertical structure

(Active/passive Optical Integration is epitaxy-driven (MBE, MOCVD))



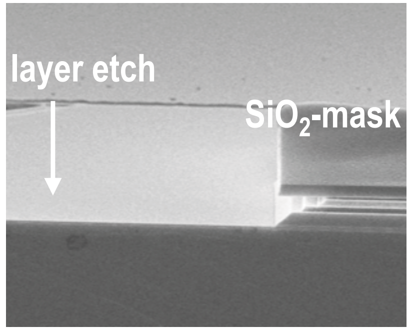
	Multiple Off-set Quantum Wells	Lateral regrowth our choice !	Quantum Well Intermix	SAG	Stacked Growth
Bandgap ΔEg	high ☺☺	high ☺☺	modest – high ☺	modest ☺	high ☺
Index Δn	modest ☺	high ☺☺	low – modest 😐	low 😐	high ☺
Doping n,p	flexible ☺☺	flexible ☺☺	difficult ☹	no ☹☹	high ☺
Design Flexibility	average / high ☺	high ☺☺	sufficient ☺	modest ☹	sufficient ☺
Active/passive	modest ☺	difficult ☹	simple ☺	modest ☺	difficult ☹
Process Complexity	modest / high ☹	highest ☹☹	acceptable 😐	low ☺	acceptable 😐

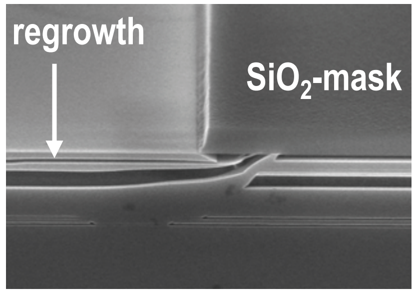
Monolithic Integrated Mode-Locked Lasers Diodes @1550nm

Generating fs-pulses from monolithic integrated mode-locked LASER diodes requires:

- *optimized fs-carrier dynamics* in nonlinear optical amplifiers and absorber
- *ultrafast absorber structure* to balance intra-band carrier transients
- *Integration technology* (multi-section epitaxial lateral regrowth)

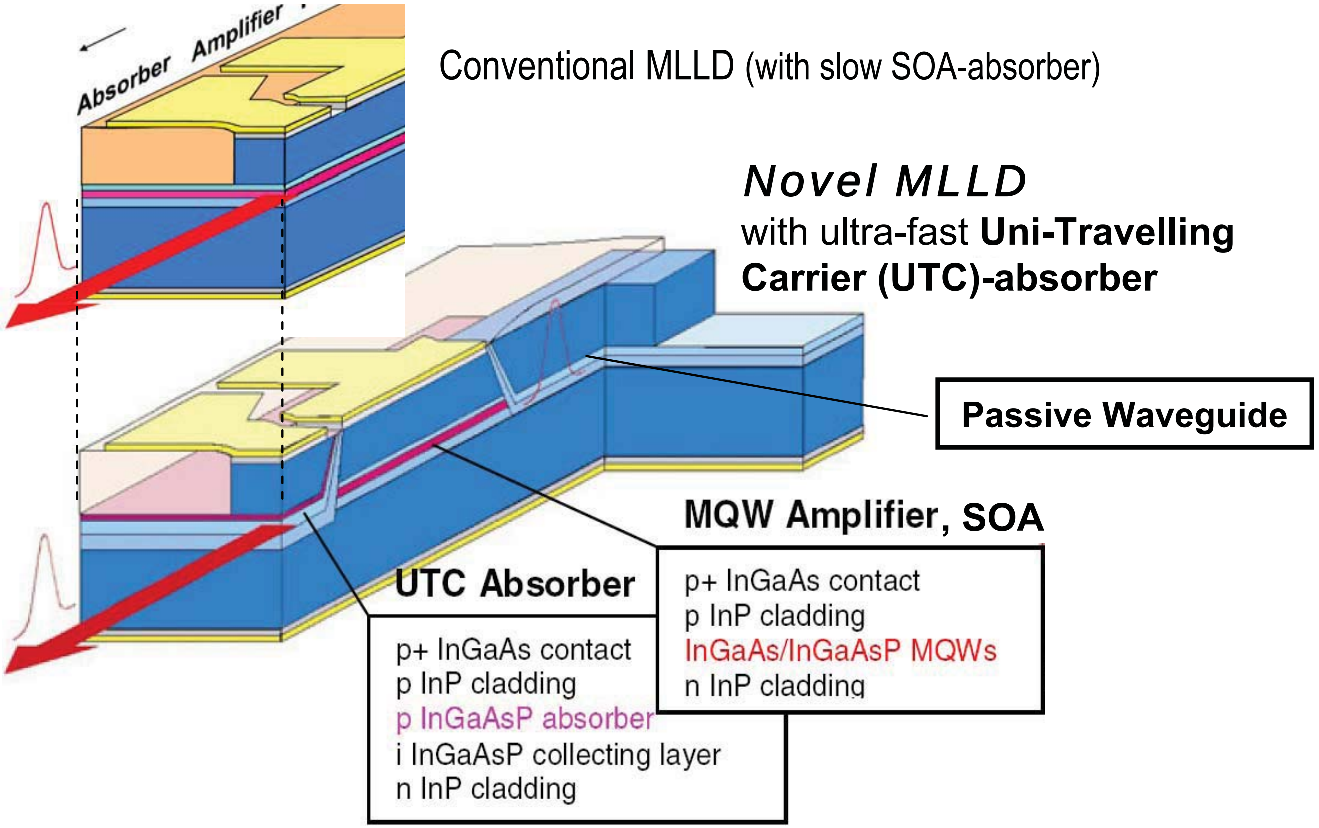
➡ **Slow absorbers limit pulse width ~2ps at low f_{rep}! → 500fs ?**



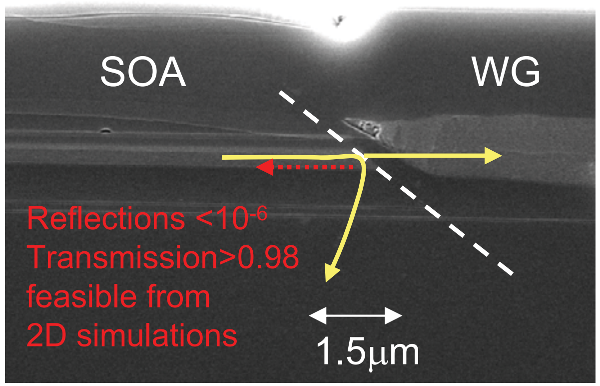


Functional Integration:

SOA + passive WG + Interfaces + Absorber / EO-Modulator (UTC)

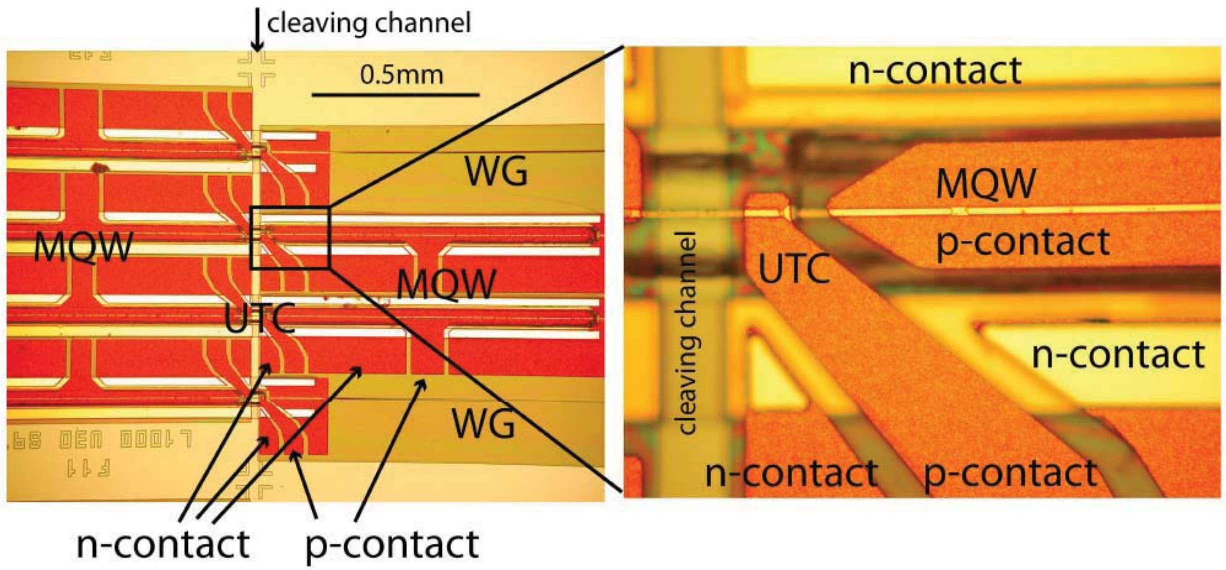


optimized tilted regrowth:



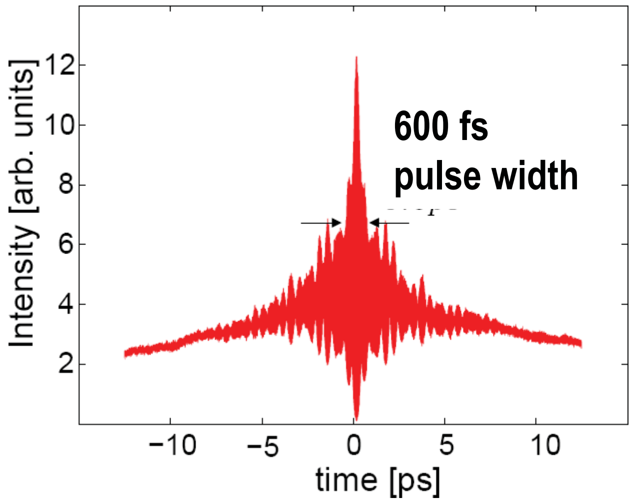
Monolithically Integrated Mode-Locked LASER Diodes for 600 fs pulse generation

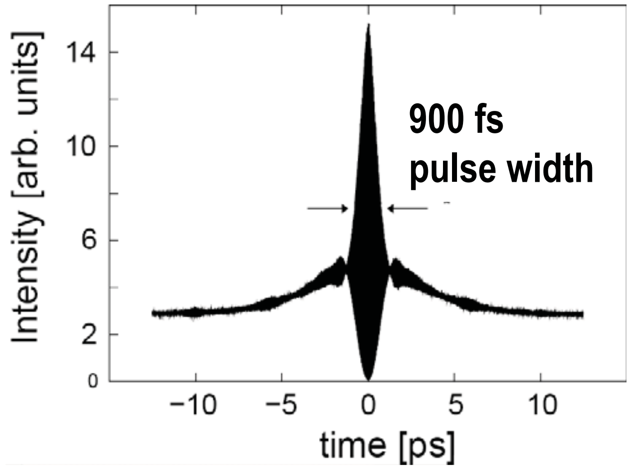
Finalized mode-locked LASER diode:



Extremely complex fabrication process with 16 mask levels and 2 month processing time

2-photon auto-correlation pulse width measurements:





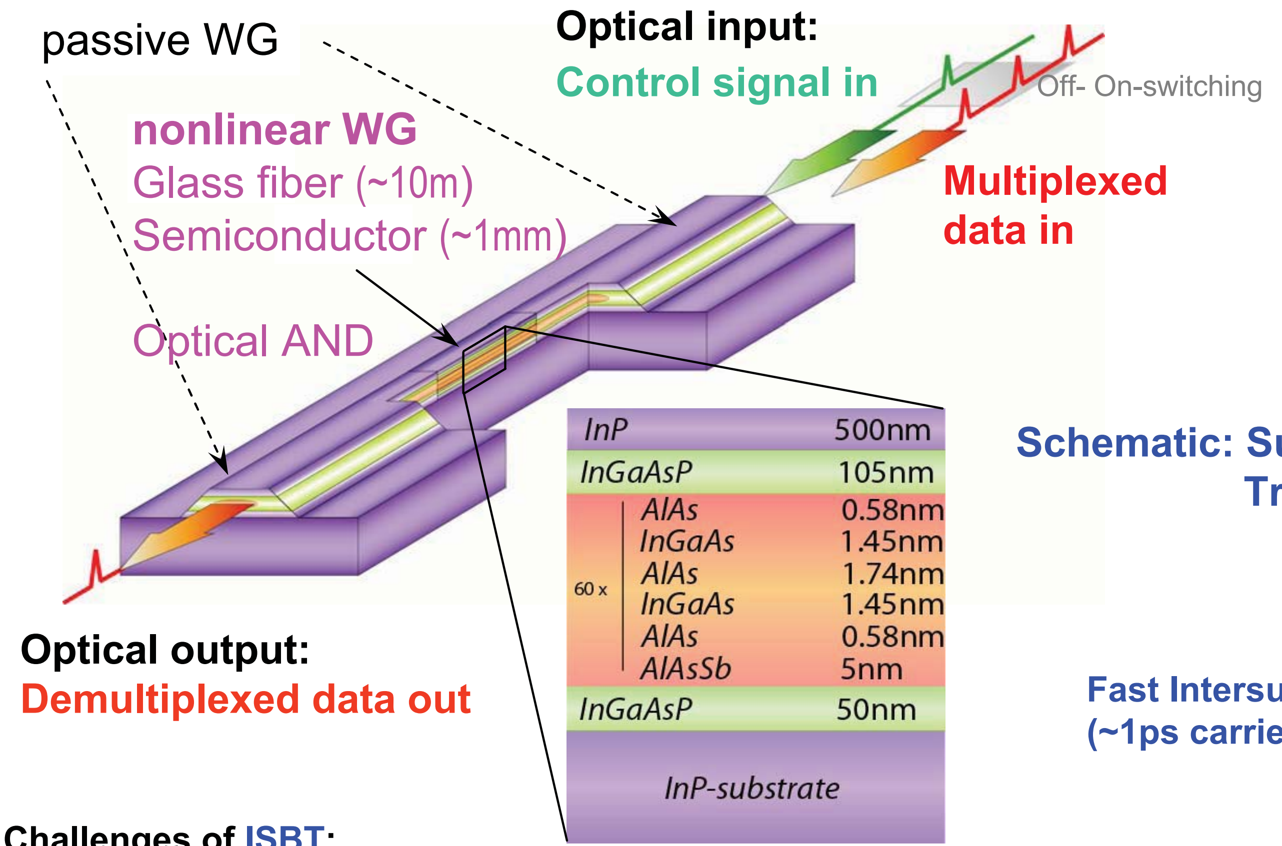
From Fiber- to Semiconductor-based Tb/s OTDM

All-Optical Switch **(AOS)** *using Intersubband Transitions with ps switching time*

- Electronics unlikely to reach sub-ps-switching times required for Tb/s OTDM processing

➡ **strong Optical Nonlinearities** in SC (instead of nonlinear fiber) have ps-time constants

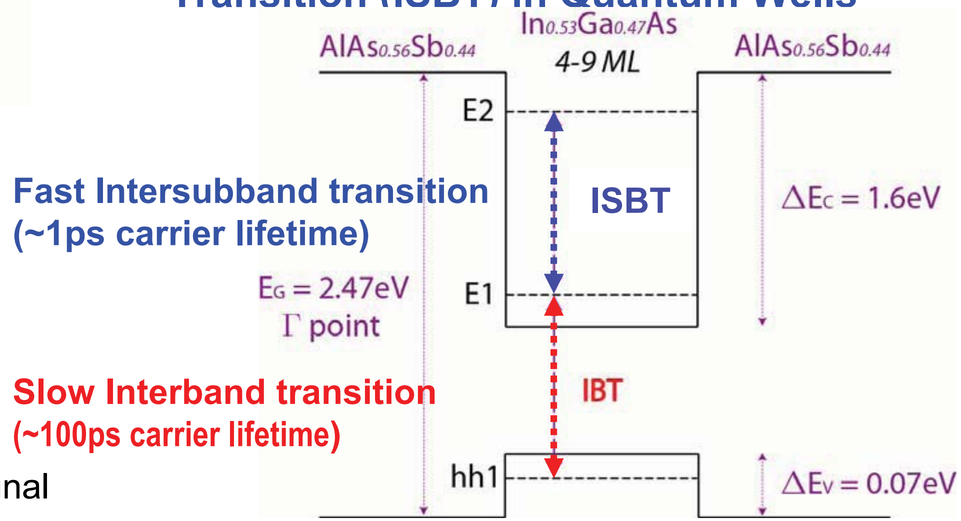
➡ **all-optical:** no conversion into the optical domain



All-Optical OTDM Key Functions requiring sub-ps switching:

- **Demultiplexers**
- **Pulse Generators**
- **Optical Clock-Recovery**
- **3R-regeneration**
- **Header Correlator**
- Optical Amplifiers

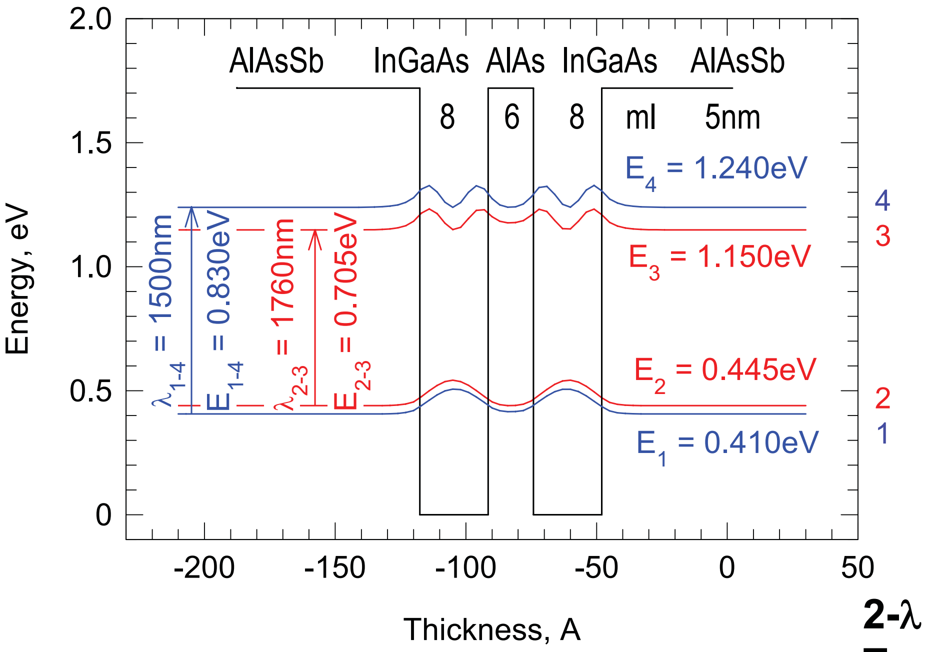
Schematic: Sub-ps All-Optical Intersubband Transition (ISBT) in Quantum Wells



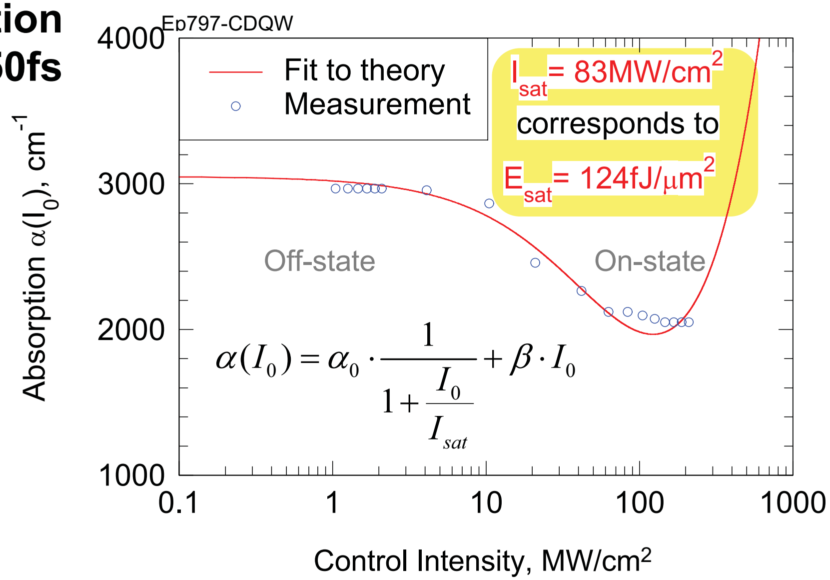
Challenges of ISBT:
- only active for TM-polarization
- challenging material system
- relative high saturation energy for on-off switching by the control signal

Ultra thin InGaAs/AlAsSb Coupled Quantum Wells

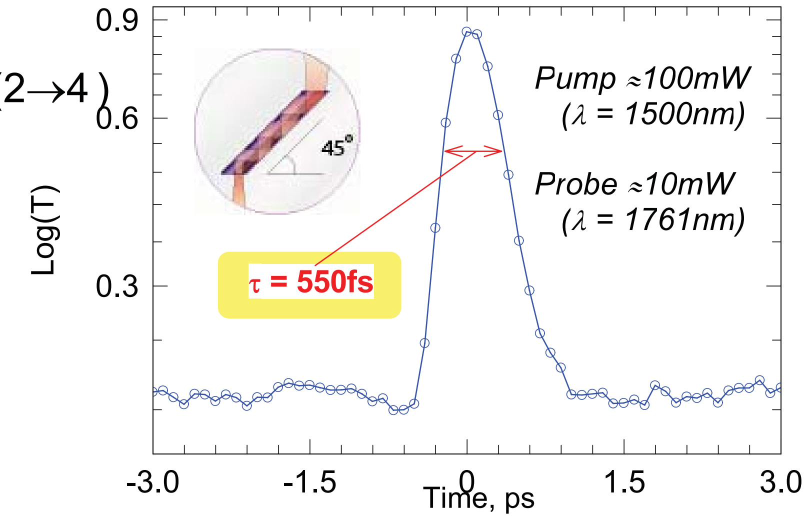
- ultra thin, deep **Double Coupled Wells (DCQW)** in ultrathin (~6-8ml) generate a **4-level system in the conduction band** to decouple the **TM-Control** (1-4 transition) and **TM-Data signals** (2-3 transition)
- Transitions 4-3 and 2-1 are ultrafast and phonon mediated ➡ ps-carrier lifetimes
- DCQW are n-doped (levels 1 and 2) with Si



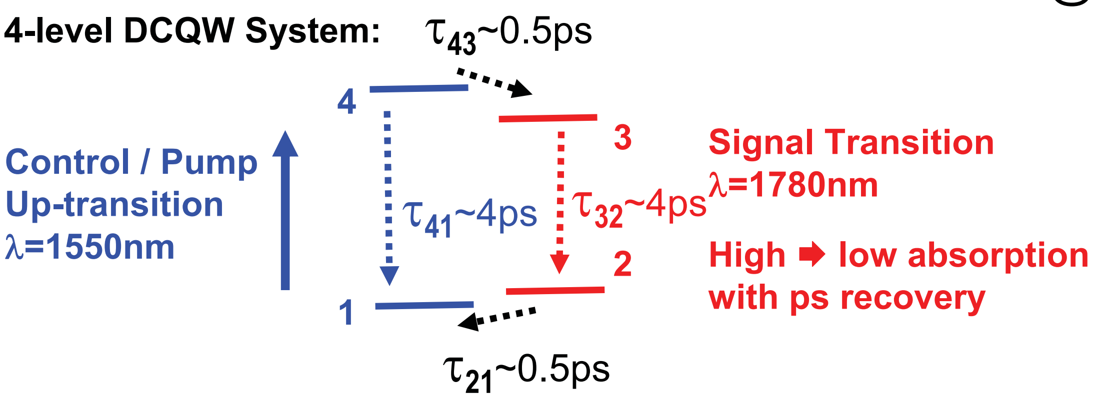
(2 → 3) Absorption saturation @ 150fs



2-λ PP-Transmission Transient @1780nm (2→4)

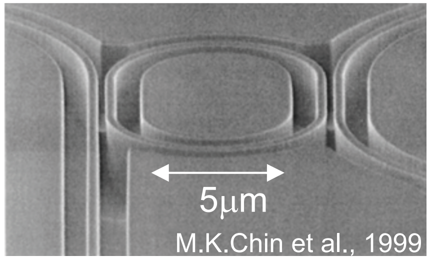


4-level DCQW System:



Densification of optoelectronic devices and ICs

mm - cm-sized devices for OICs based on low contrast (Δn) waveguides are **interconnect-limited**!
Large bend radius of WGs r~1/Δn ➡ Density ~1/r² ~ Δn²



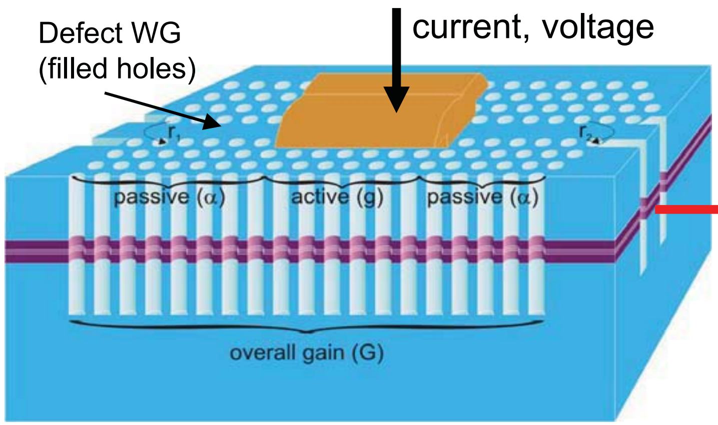
Solution 1: *High contrast WG , Photon wires*

➡ increased Δn-contrast (~2) by air/semiconductor interface

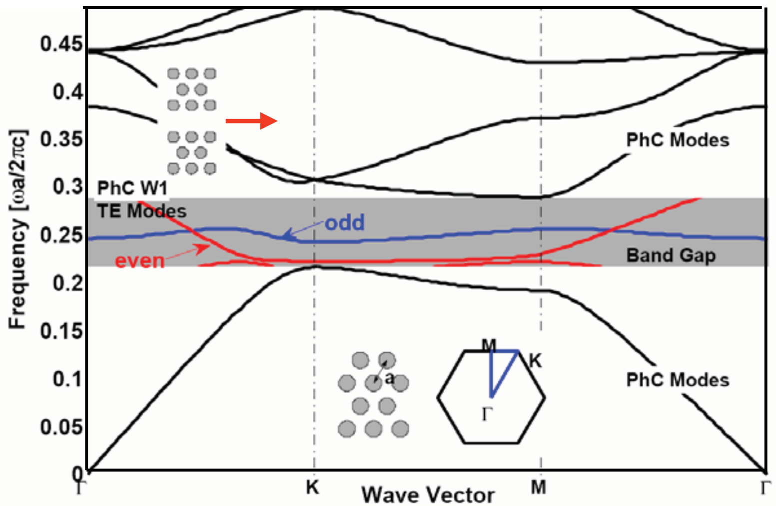
Solution 2: *Planar photonic Crystals (PhC)*

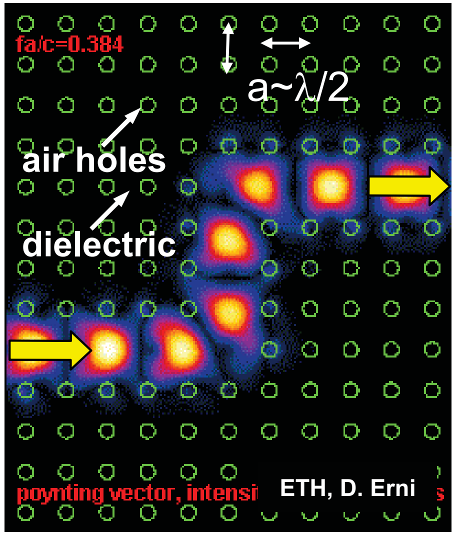
➡ strong lateral Light Confinement / Guiding in a defect waveguide by the planar **Photonic Bandgap** of a 2D grating (but weak vertical confinement !)

Planar InP/InGaAsP PhC with Defect WG:



Dispersion Diagram ω(k):



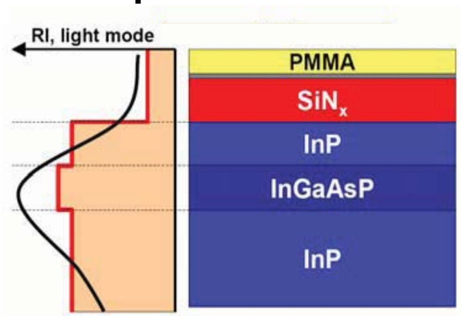


Advantages of PhCs:

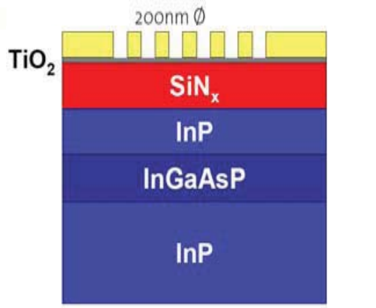
- ➡ wave length size bend radii reduce device size and interconnect area to a ~10λ²
- ➡ **dispersion engineering** ➡ low group velocity and **"slow light, stopping of light"**
- ➡ **strong nonlinearities** by temporal (slow light) and spatial power confinement
- ➡ carrier life time engineering, Purcell-Effect

InP/InGaAsP-Photonic Crystals: Process Flow

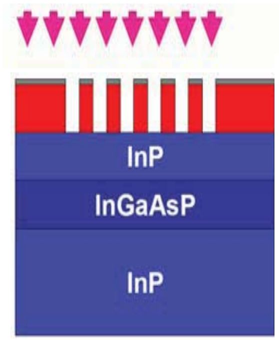
① SiN/Ti-hard mask, EBL-resist deposition



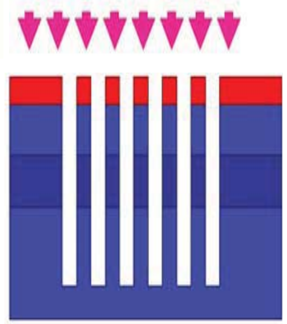
② EBL+PEC PMMA patterning



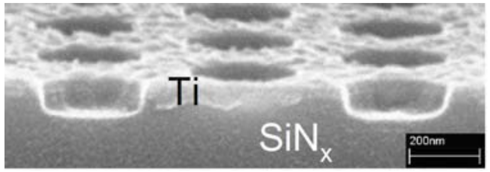
③ RIE of hardmask



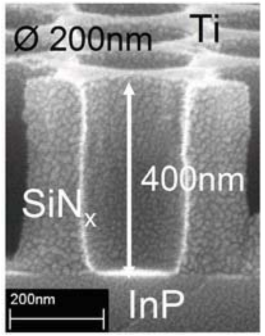
④ ICP-RIE of GaInAsP



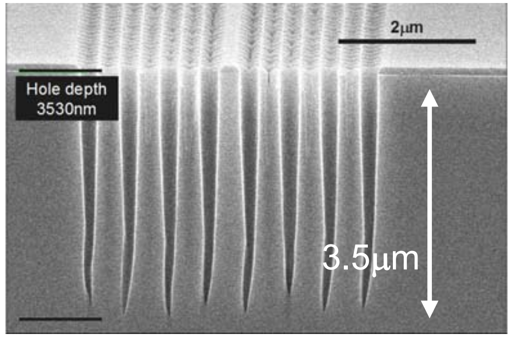
③a



③b



④



***Major Process Characteristics*:**

- **proximity corrected e-beam litho** (30kV)
- max. PMMA thickness <300nm
- **SiN_x/Ti hard-mask**, max. reliable etched thickness 400nm

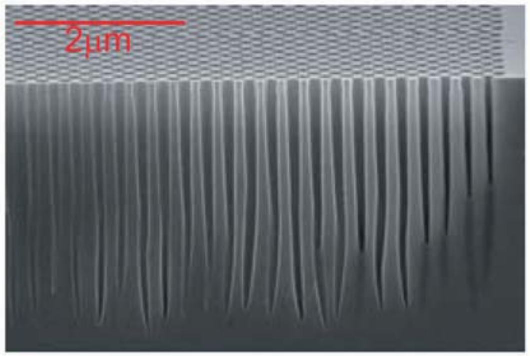
} ①

- **SF_6-, CHF_3-based RIE etching** of hard-mask

} ③

- **optimized $Ar/Cl_2/N_2$ ICP cyclic etch** chemistry for deep holes:
  Ar: physical etching
  Cl_2: chemical etching
  N_2: hole sidewall passivation, shape control

} ④

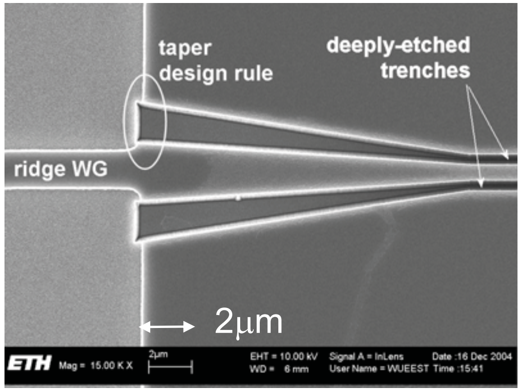


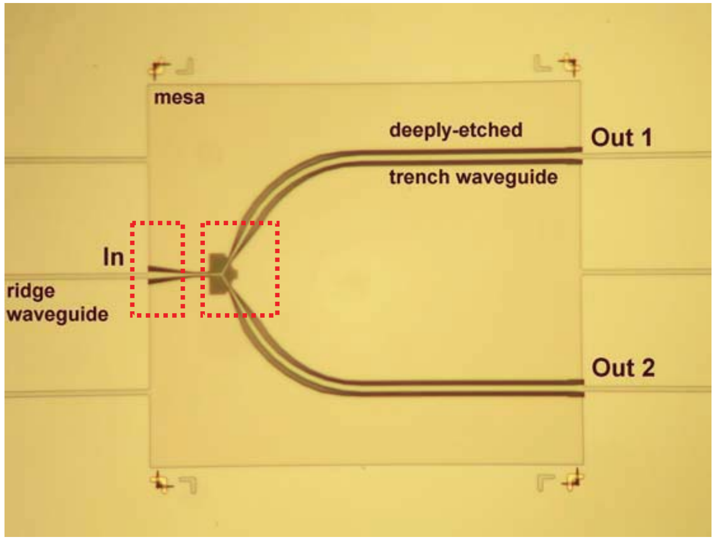
Interfacing Photonic Crystal: Power Splitter

Mix&Match-lithography (optical and e-beam litho) ➡ **interface to fibers-PhCs**

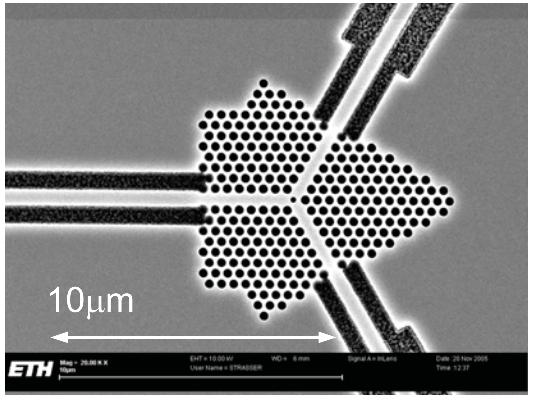
shallow ridge (width=1.5μm / height=300nm) ➞ deep trench (w=0.5μm / h=3μm) WG ➞ PhC WG

Optical ridge WG **EBL Trench ridge WG**

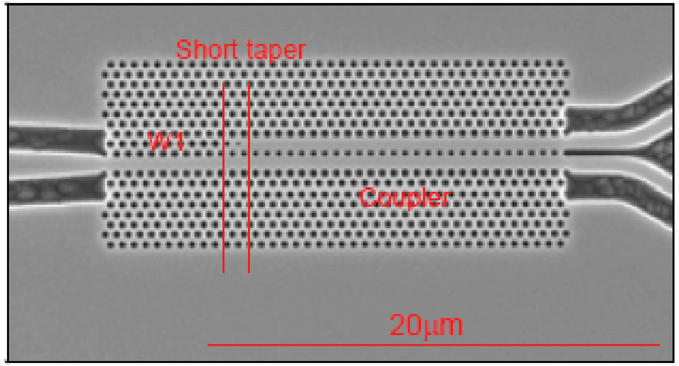




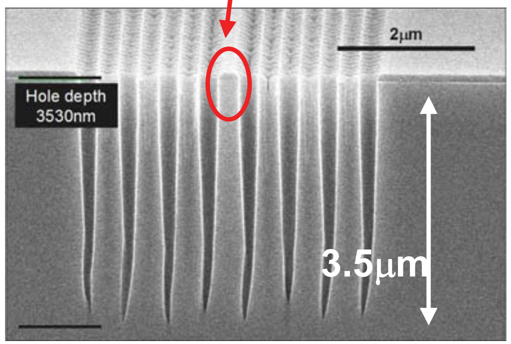
Optimized PhC-splitter:



Compact directional coupler:



PhC-hole lattice in InP/InGaAsP
by e-beam lithography and dry etching



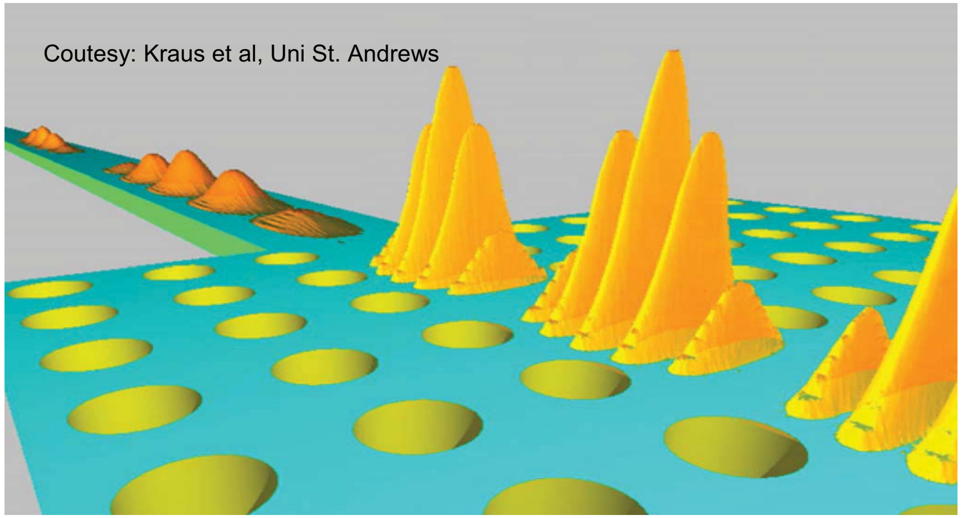
Conclusions and Outlook:

- **High Speed InP- and SiGe Electronic** is progressing towards +160 Gb/s
- **OWDM** with advanced coherent modulation techniques is approaching the fiber capacity
- **OTDM** lags in capacity, but OTDM/OWDM still promises system simplicity
- **Tb/s All-optical Routing** is still far out and dependent on optical integration
- **Photonics and Optoelectronics Integration** & Miniaturization has progressed slowly despite its crucial role for the widespread proliferation and economic success of Tb/s-communication
  ➨ there is still not enough “Photonic Moore”

- **Silicon Photonics** is attractive and progressing even “without” an efficient light source/amplifier
- **Nano-Photonics** (Photonic Crystals, Plasmonics) could be useful for ultimate downscaling
  - but who needs optical ULSI if we hardly manage SSI - MSI device density
  - novel technologies should be functional complete and competitive against existing solutions
- **Proven CAD-tools** required for spreading of the technology
- Lack of a **Generic Technology platforms and Foundries** is slowing down progress

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Thanks for your attention !



Thanks to all my current and past PhD-students !

Collaborations:

École Polytechnique Fédérale de Lausanne; IBM Research Zurich Research Laboratory; FIRST Center for Micro- and Nanoscience; nano-optics; Raith; zma Fachhochschule Aargau Nordwestschweiz FHA

Project fundings: NSF NCCR Quantum Photonics-, ETH-TH-, ETH-INIT-Grants, ePIXnet EU-Grant:

Schweizerischer Nationalfonds / Fonds national suisse / Swiss National Science Foundation; quantum photonics; ETH Eidgenössische Technische Hochschule Zürich / Swiss Federal Institute of Technology Zurich; ePIXnet; KTI CTI; CAS Center for Advanced Silicon Electronics