Quantum Dot Lasers:
A Step Toward Easier Integration with PICs

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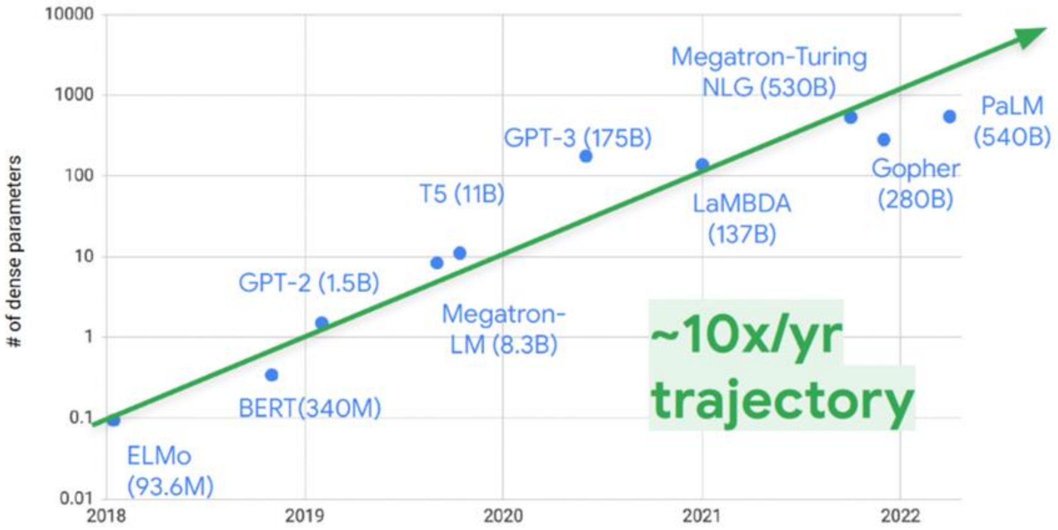
EPIC Online Technology Meeting on Integrated Photonics Manufacturing with TOSIA

October 29, 2024

Outline

- Development of cost effective and reliable Photonics Integration Technology
  - The major key to bring Photonics to the highest volume ever existed
  - Billions of 200Gbps channels will be needed per year soon
- Technology landscape and competition
- Quantum Dot Lasers and Innolume GmbH
- QDs: Unique features and products enabling effective integration
  - Temperature stability
  - Extended reliability with no early-life failures
  - Optical Isolator unnecessary
  - Multi-λ chips: DFB arrays, Comb-lasers and WDM SOAs
  - GaAs vs InP

Generative AI Changed Everything



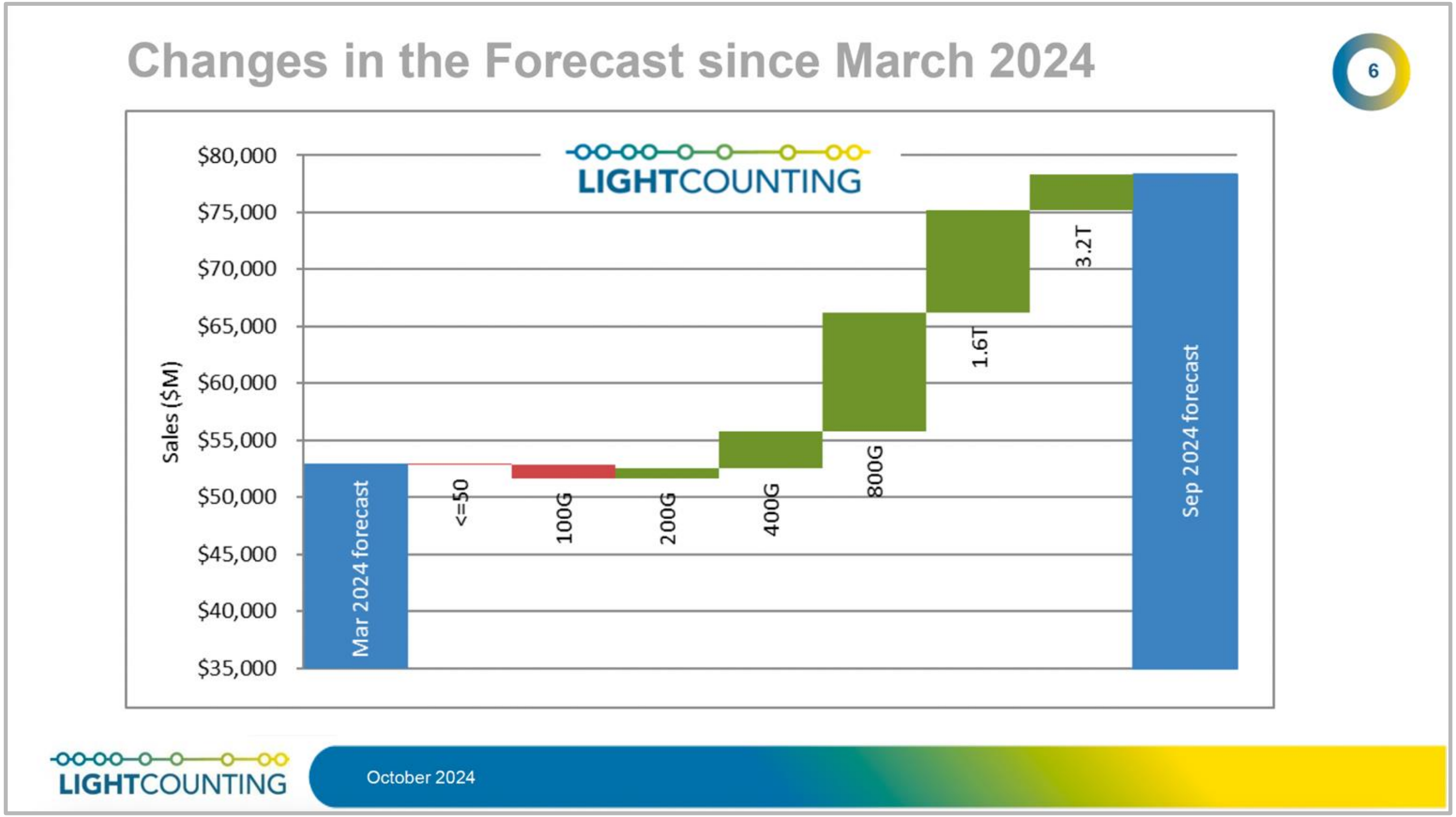
ChatGPT 4.0 Model Size > 1T Parameters

Iso-Silicon performance increasing 2X / 2 Years

Large Language Model sizes are increasing 10X per year
Iso-Area Silicon performance is improving - 2X / 2 years

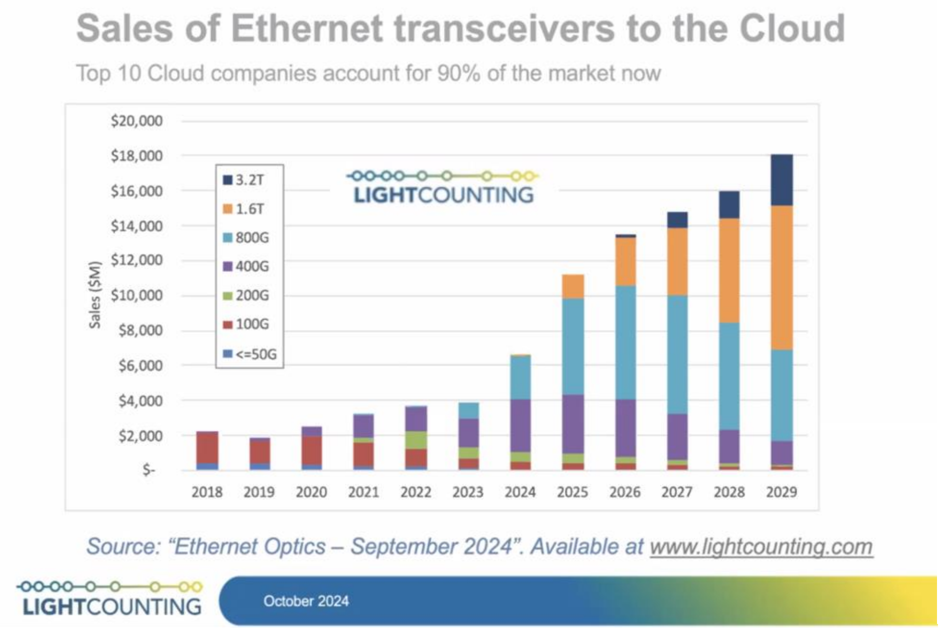
Market forecasts are being reconsidered every 6-8 months toward higher volumes

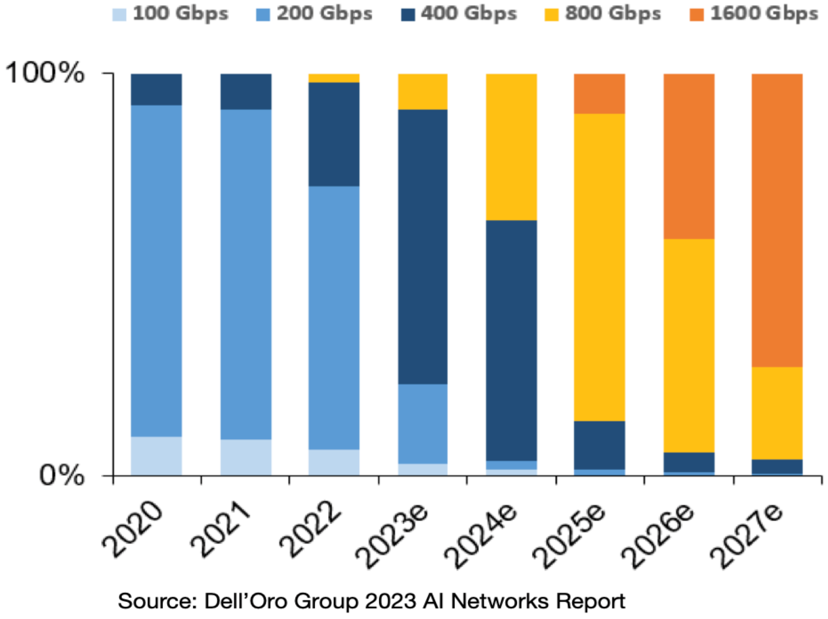
INNOLUME



Transition to 1600G (8x200G lambda)

INNOLUME



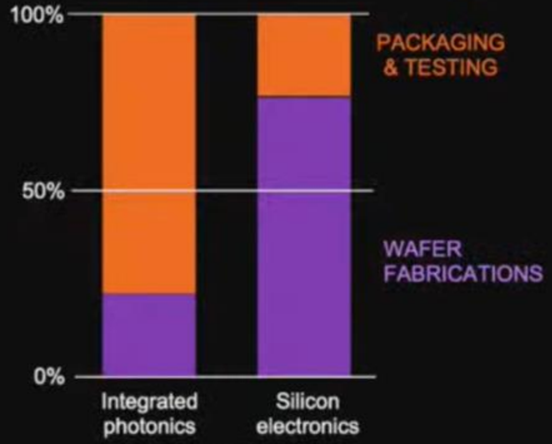


<u>Our view:</u>
Lightcounting Forecast October 2024, which is too low and way too conservative on speed of 1600G Transition

Dell'Oro Forecast 2023 – 1600G will ramp to Volume in 2025 and dominate by 2H2026

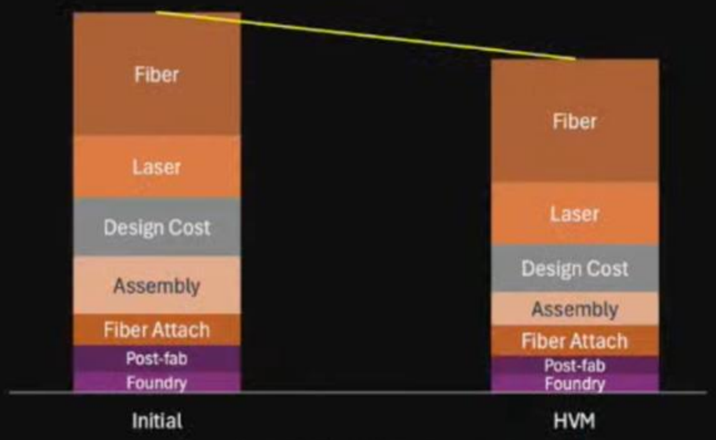
#5: Driving SiPh Products to Semi Cost Structure

Share of fabrication versus assembly costs



Source: OIDA

Cost trending for scale-up in the foundry



Based on internal GF cost modeling

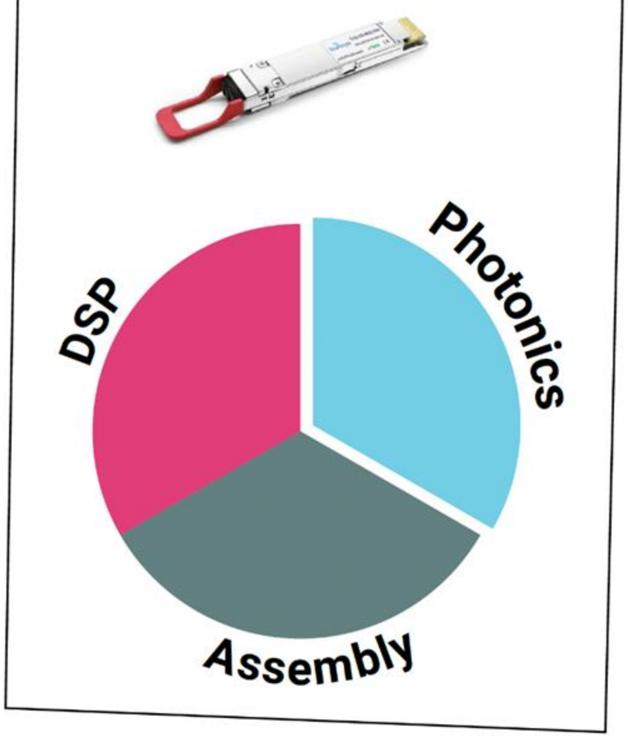
Top drivers for silicon photonics cost-down:

- Cost per fiber and fiber bundling / automation
- Electrical / optical testing
- Laser costs

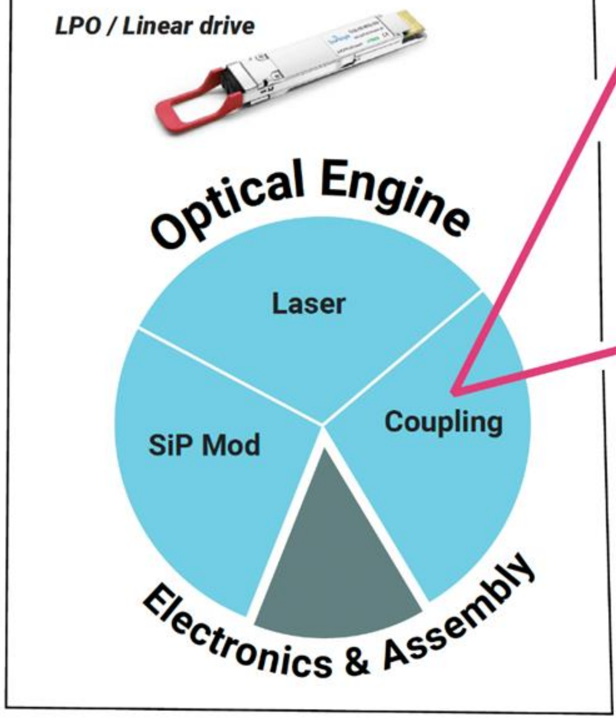
Envisioned Optical Transceiver evolution

INNOLUME

Current value distribution



Value distribution in 3Ys

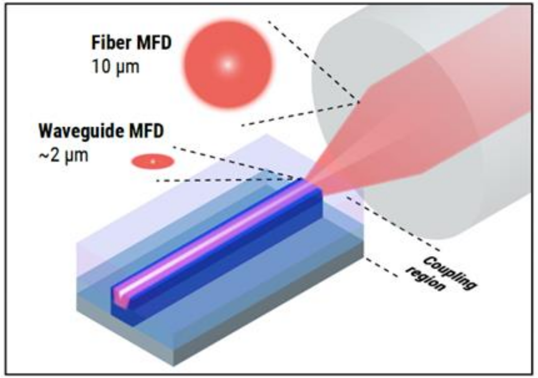


- *Laser integration with SiPh modulators is one of 3 most important components for future Optical Engines*
- *The issue is not solved yet in HVM fasion (except of Intel SiPh)*

Coupling methods landscape

INNOLUME

Edge coupling



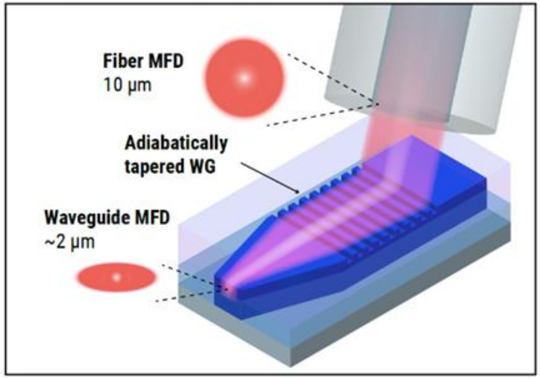
Pros

- Highest efficiency
- Large bandwidth (~ 100 nm)
- Optical port scalability
- Easy manufacturing process
- Polarization insensitive

Cons

- More complex and costly as of today **especially for the arrays!**
- No on-wafer testing possible

Vertical coupling



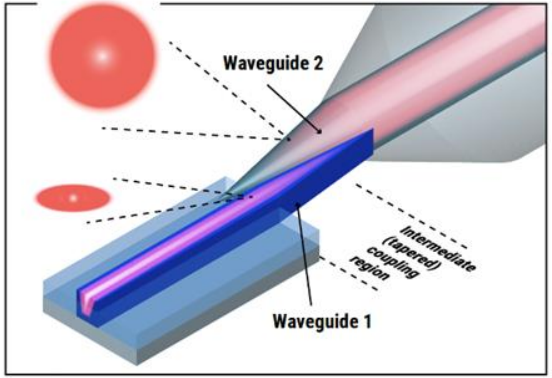
Pros

- Passive alignment possible
- Coupling fixture can be pluggable
- Optical port scalability
- Easy manufacturing process
- On-wafer testing possible

Cons

- Narrow bandwidth (~ 30-40 nm)
- Polarization sensitive

Evanescent coupling



Pros

- Wafer scale manufacturing process
- No alignment required
- Heterogeneous integration of III-V-on-Si
- Native on-wafer testing

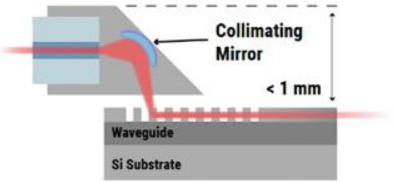
Cons

- Low power coupling only
- Complex taper region design
- Extremely sensitive to the displacements

Overview of current coupling solutions

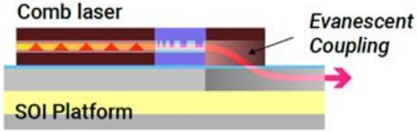
Passive PIC-to-SMF

- **V-grooves**
  active final alignment
- **Optoscribe**
  DLW process, before placement
- **Cudoform**
  acquired by Senko, Dec'22
- **Teramount**
  Polymer-on-Si beam expander
- **Broadcom**
  Bulk beam expander



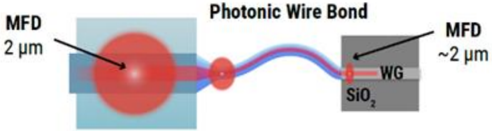
Passive Laser-to-PIC

- **Laser diode Flip Chip**
  p-side down on pedestal
- **Micro-Transfer Printing**
  both edge-to-edge and evanescent



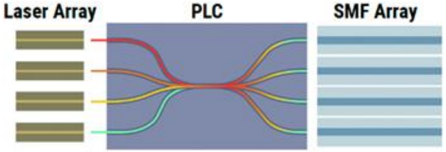
to-PIC & to-SMF

- **GlobalFoundries**
  Heterointegration:
  Passive Flip Chip + V-grooves tech
- **Photonic Wire Bonding**
  Polymer: scalability & degradation issues



Multi-port remote Light source

- **AyarLabs SuperNova™**
  Planar Lightwave Circuit



Main challenges

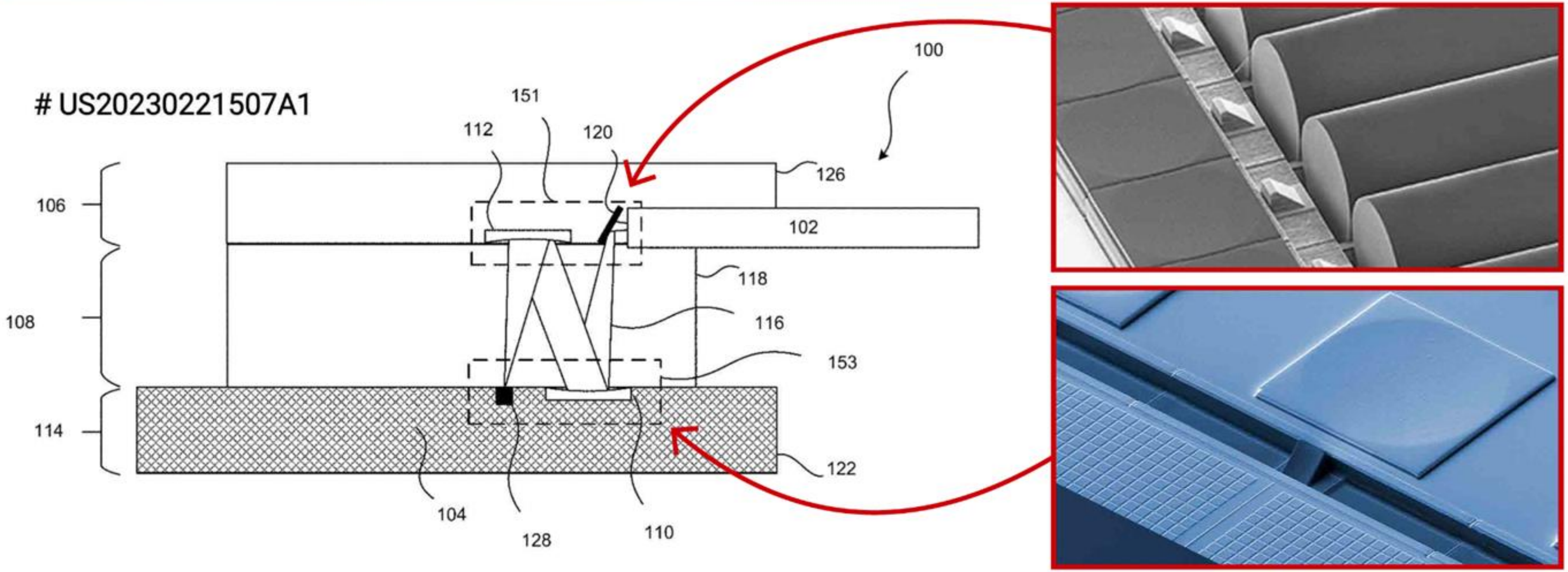
- **Avoid active alignment**
- **High yield, Robustness**
- **Couple arrays, provide multi-lambda channels**

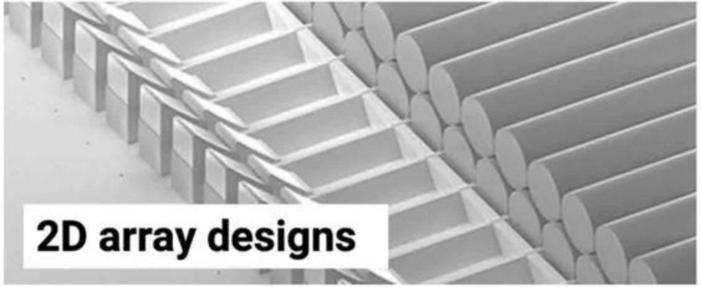
Also to consider

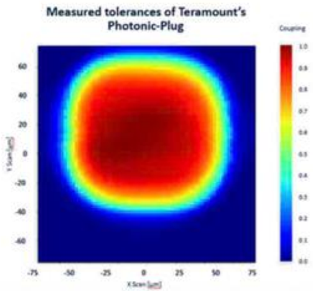
- High power device coupling
- 2D arrays arrangements
- Dense integration of active photonics on ICs
  due to the large footprint of the photonic devices

Polymer beam expander by Teramount

US20230221507A1

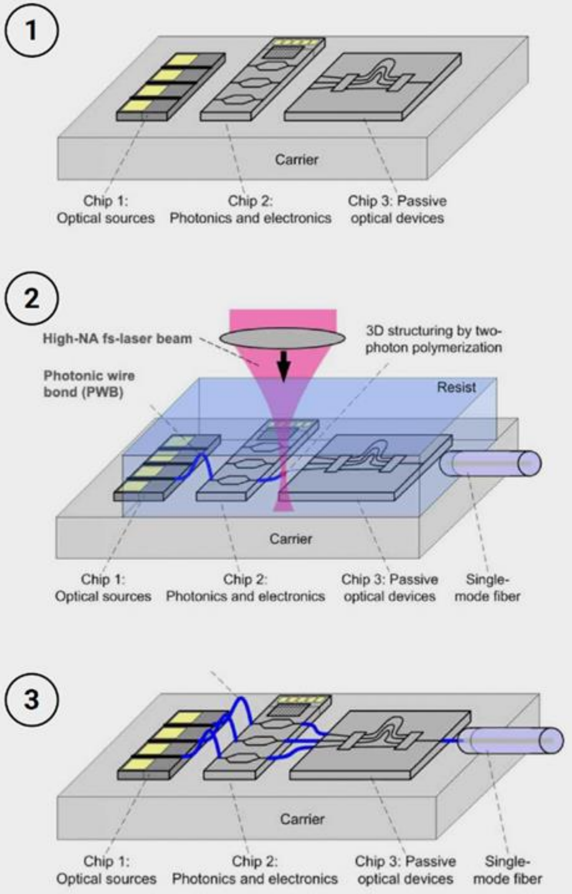


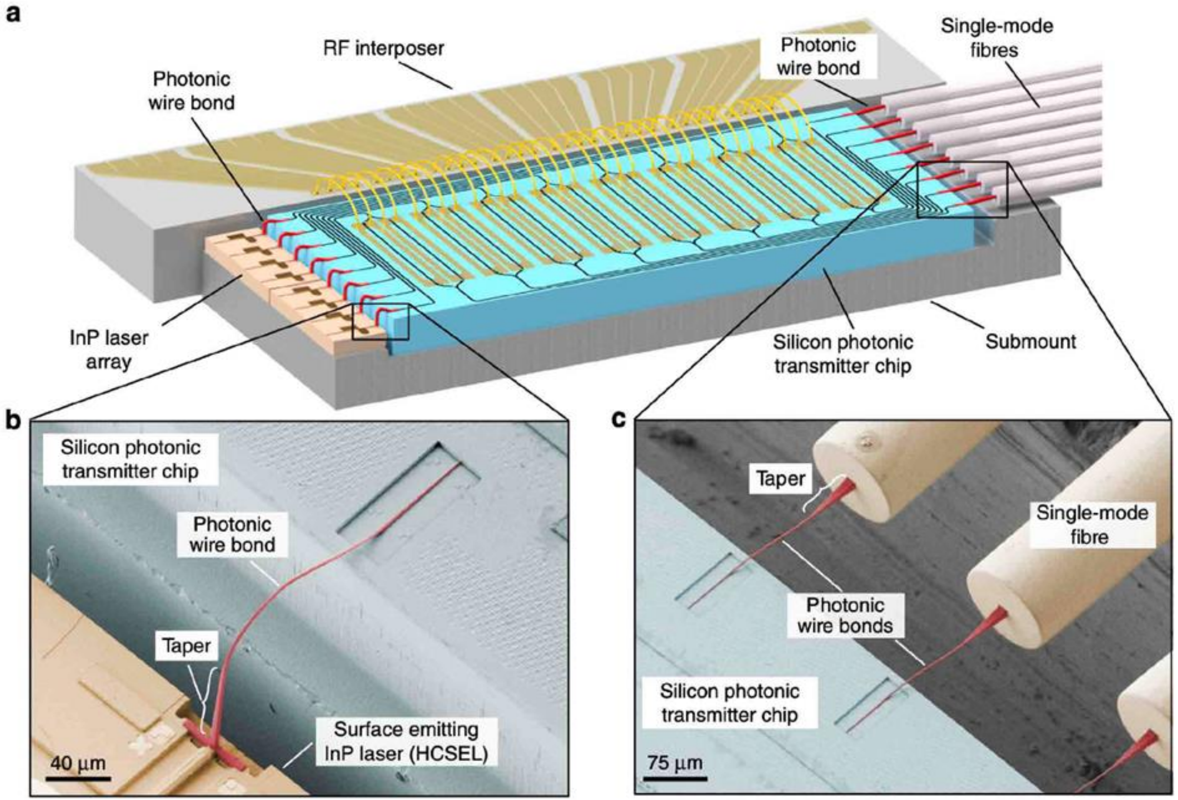




Losses < 0.5dB @ Misalignment ±30 µm

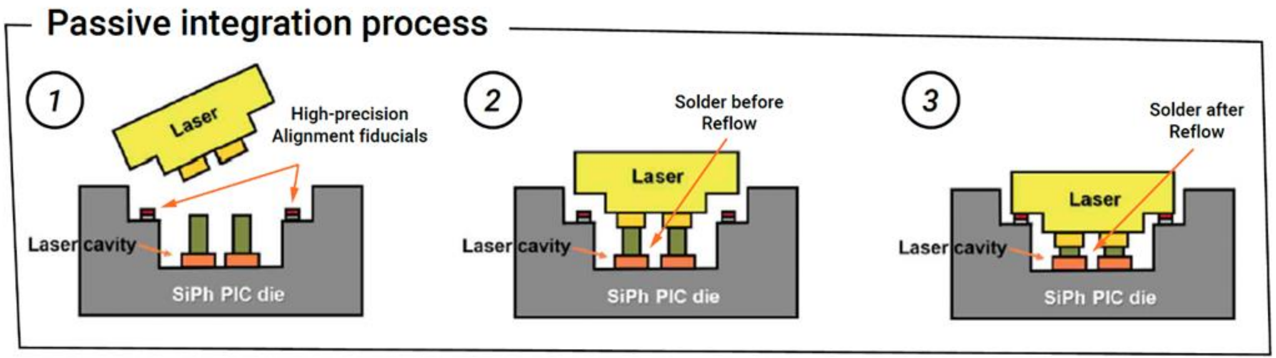
Photonic Wire Bonding by Vanguard Automation

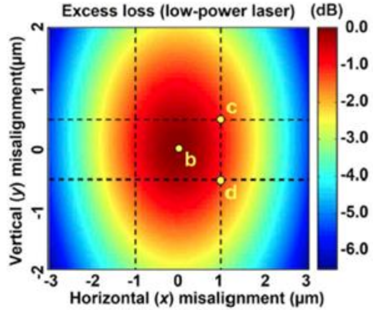




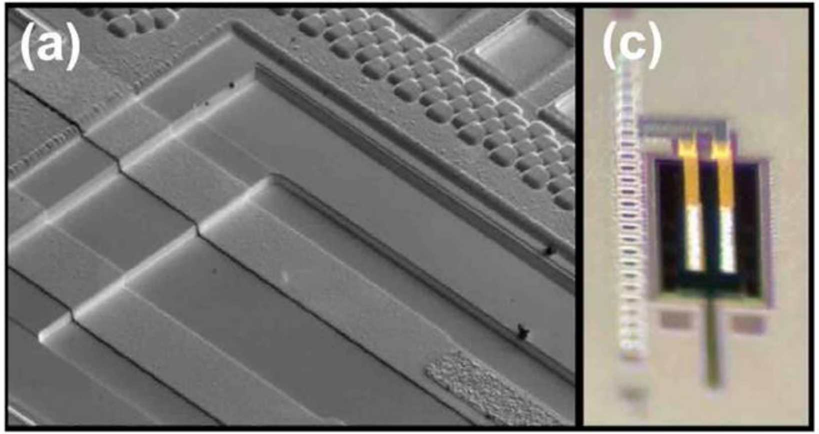
Blaicher et al. Light: Science & Applications (2020)9:71 // https://doi.org/10.1038/s41377-020-0272-5

Passive Flip Chip integration // *Passive alignment*

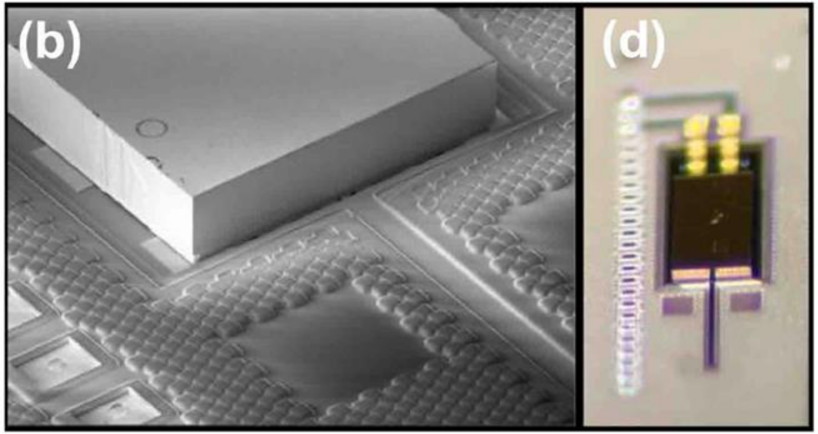




Horizontal misalignment ± 1 μm
Vertical misalignment ±0.5 μm
Losses due to misalignment 1.2 dB

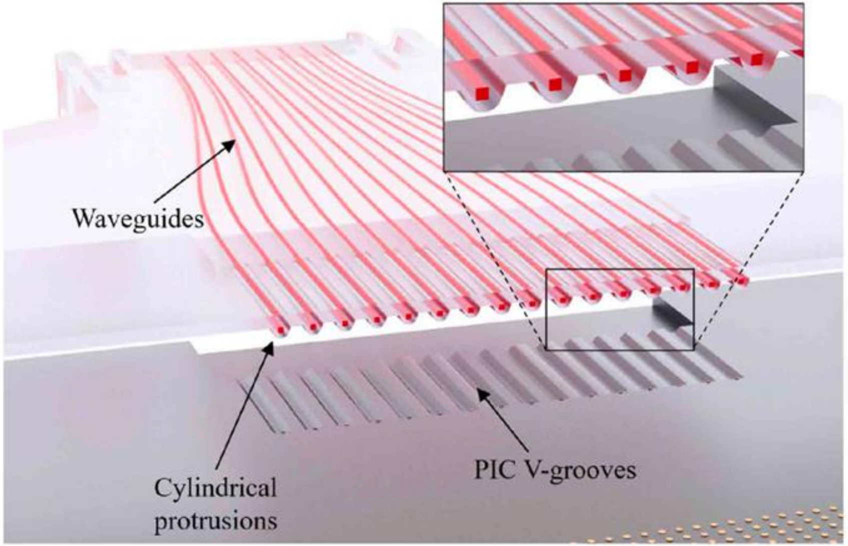


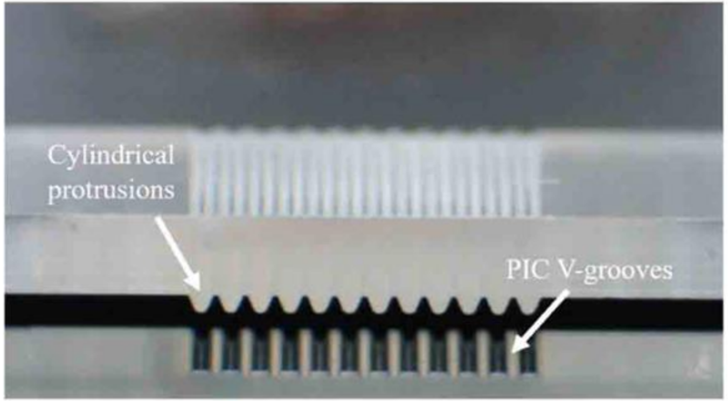
(a), (c) Laser cavity before integration, SEM and optical images

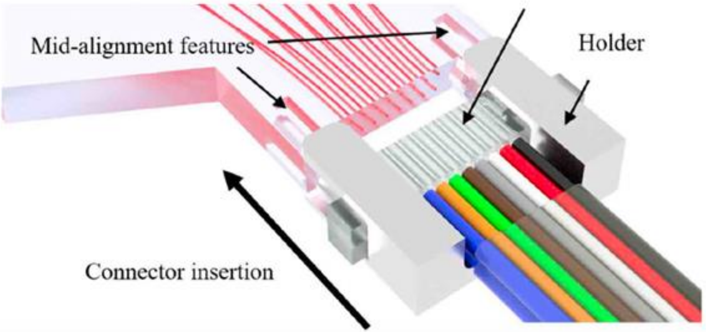


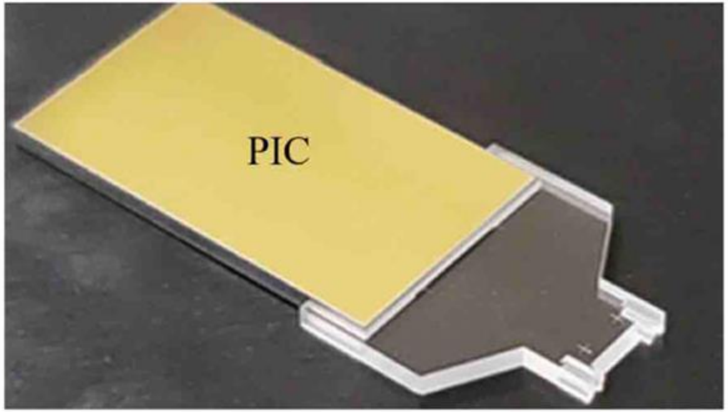
(b), (d) Laser cavity after integration, SEM and optical images

Pluggable fiber fabric attachment by Intel









Psaila, Nicholas, et al. "Detachable Optical Chiplet Connector for Co-Packaged Photonics." Journal of Lightwave Technology (2023)

Technology landscape

Modulation: PAM4

GaAs - VCSELs
100G today
Share will decline with 200G due to reliability

InP - EML
Leading share today but losing share to SiPh
Due to cost, reliability and module assembly yield

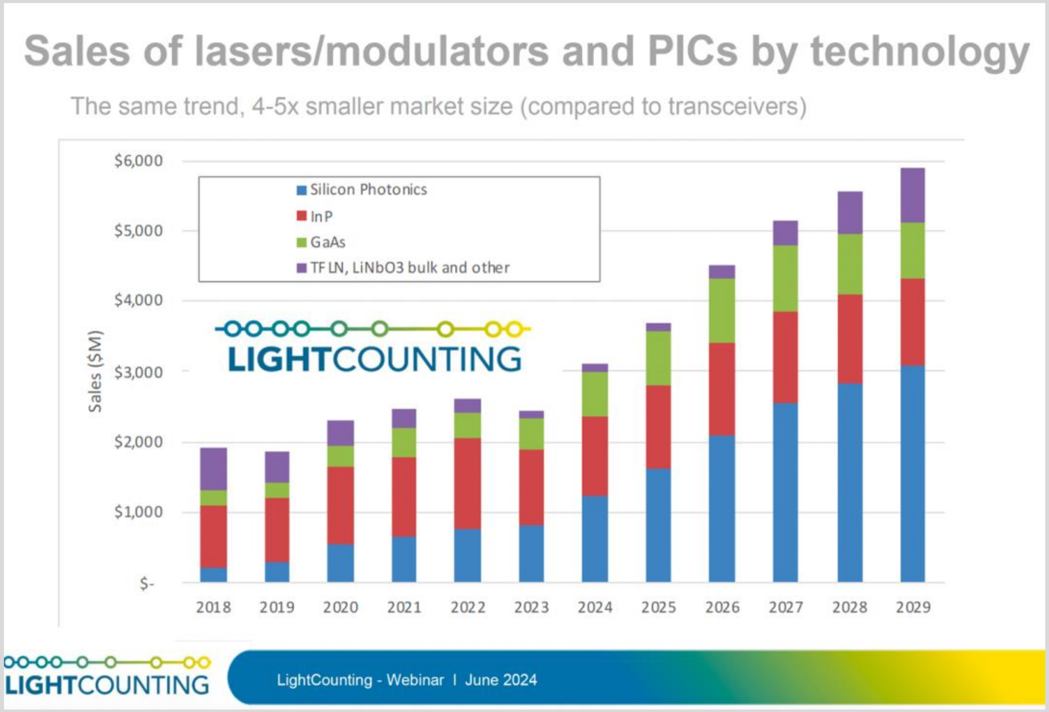
SiPh
"CW DFB + PIC + integration: laser→PIC,
PIC→ FAU (fiber) = Optical Engine (or Light Engine)

800G DR8 and 2xFR4 ramping now with SiPh MZM
1600G (8x200G) ramping in 2025

CW DFB - InP today,
GaAs QD is the better alternative but need to ramp

Passive integration is a very big challenge

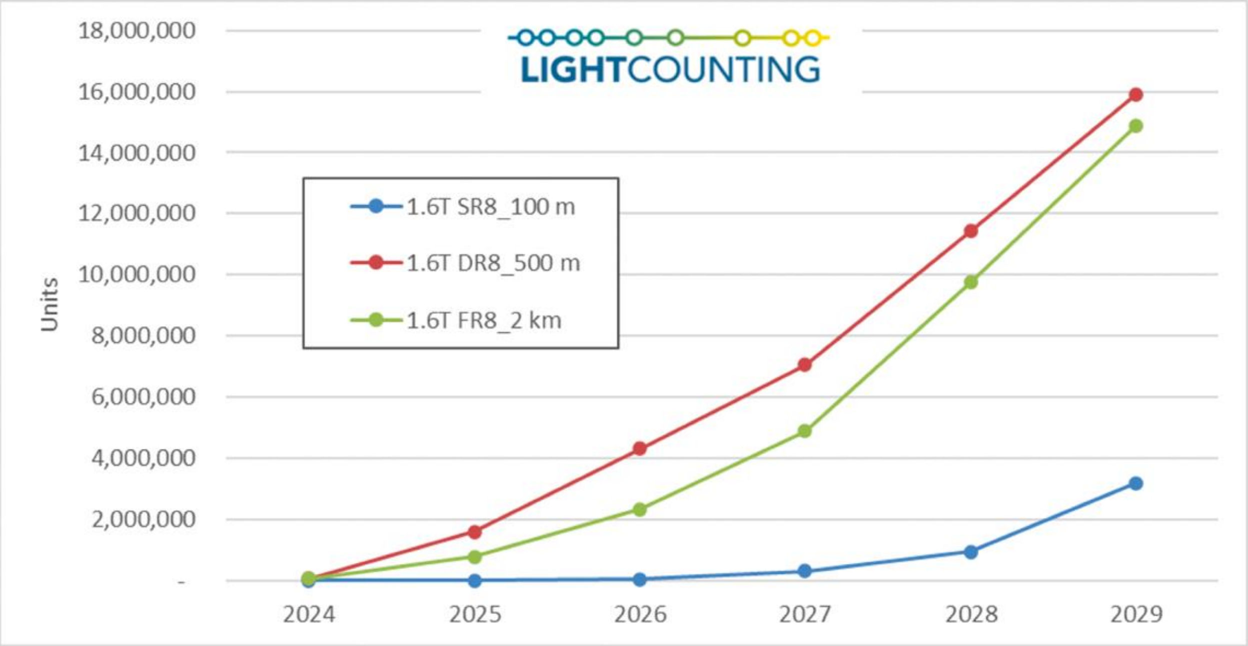
TFLN:
Leading technology for 3200G (8x400G-PAM4)



<u>Our view:</u>
This Lightcounting forecast from July 24 is outdated (too low). Growth of bandwidth for AI fabrics is projected to be 10X over the next three years, primarily for 1600G (8x200G) optics. SiPh will be the leading share gainer going forward.

Forecast for 1.6T transceivers

Improved outlook for 200G VCSELs and SR8, but 2xFR4 and DR8 will dominate the market



Source: LightCounting

30 years of R&D, 20 years of production

INNOLUME

1963
Ioffe Institute

Invention of **Heterostructures**

Double Heterostructure
Zh.Alferov, R.Kazarinov, USSR Patent, N950840

independently
Single-Heterojunction
H.Krömer, UCSB

1968
Ioffe Institute

First diode laser at RT

Zh.Alferov and the team

One month ahead of Bell Lab

1981
Ioffe Institute

First semiconductor **Quantum Dots**

A. Ekimov, A.Onushchenko, JETP Lett.

1994
Ioffe Institute
Technische Universität Berlin

First QD diode laser

N.Kirstaedter et al., El.Lett.

2000


Nobel Prize in Physics "for basic work on information and communication technology" incl. **Semiconductor Heterostructures**

Zh.Alferov, H.Krömer, J.Kilby

2004
INNOLUME

Start of the operations

First temperature independent diode laser

S.Fathpour et al, APL

2007
INNOLUME

First Broad-band laser and **Comb laser**

A.Kovsh et al, Optics Lett, A.Gubenko et al, El.Lett.

2020
INNOLUME

Received: PRISM AWARDS

for developing **1.3 µm high power high temperature DFB laser**

2022
INNOLUME

Ultralow noise WDM SOA

2023

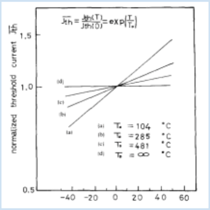

Nobel Prize in Chemistry for for the discovery and development of **Quantum Dots**

M. Bawendi, L. Brus, A. Ekimov

Progress: Why so slow? : QDs are slow!

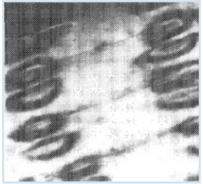
1980 — 1990 — 2000 — ZIA Lasers — Innolume — QD Lasers — 2010 — Ranovus — Quintessent — 2020 — 2025

1982
Simple theory: QD laser



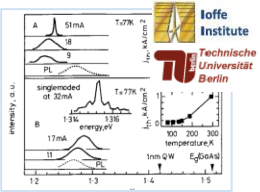
Arakawa, Sakaki, APL

1985
Observation of InAs QDs



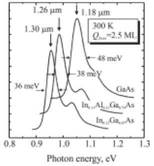
Goldstein et al, APL

1994
Room Temp QD lasers

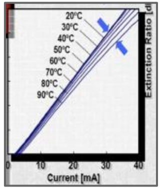


Kirstaedter et al, EL

1998 - 2002
Battle for 1.3um



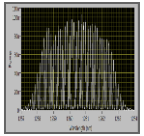
2000-2003
Battle for1.3um
VCSEL



INNOLUME
QD LASER

2004-2005
temperature
insensitive

INNOLUME



2004-2008 Mode-Locked
and Comb Lasers

Predicted advantages:

- Temperature stability
- Reduced sensitivity to back reflection
- Multiple wavelength generation (
- Narrow lasing linewidth
- Low noise (SOA and Laser RIN)
- Improved reliability

We have been waiting for maturation of external modulation technologies (SiP, TFLN) since:

- ➔ **Damping of relaxation oscillations in QDs: DML 10G+ not possible**
- ➔ **Gain / Abs is low: EML not possible**

All expected features and advantages are getting proven in production mode

QD lasers Hype Cycle

Innovations

Peak

Disillusion

Productivity

Innolume & Axalume

- *Dortmund, DE:*
  III-V Laser Fab and testing facilities
  two production MBE reactors, each 3x4" wafers per run
- *San Diego, CA:*
  SiPh design and measurement lab
- Cash-positive,
  70 FTE (incl. 22 PhD and 3 DCs)
- > 100 customers world-wide (Y2023)

Attracted Smart Money investment from Silicon Valley

Significant CapEx expansion program in Y2024, incl. new MBE machine;

Engaging with high-volume GaAs contract manufacturers for wafer processing

Team

- First in the world who brought QD lasers from research to the real markets
- Invented and developed the first QD Comb-lasers in 2007
- Developed proprietary GaAs DFB tech without overgrowth
- Pioneered SiPh µ-ring technology starting from 2004

Revenue split:

50% Unique InAs/InGaAs/GaAs QD lasers @ 1.1 - 1.35 µm

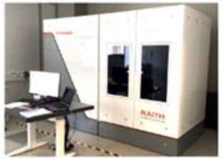
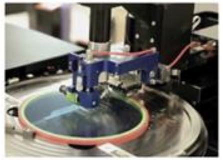
50% InGaAs/GaAs QW lasers @ 0.8 - 1.1 µm
successfully competing with world leaders

Contracts:

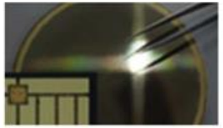
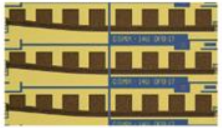
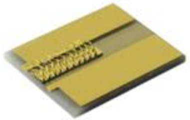
US Navy, DARPA, and NSF

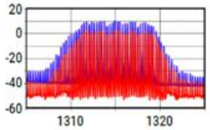
DESIGN	EPITAXY	WAFER FAB	CHIP FAB	PACKAGING	CHARACTERISATION
Software based chip design	MBE growth	Lithography Thin-film Etching Metal deposition	Chipping, Optical coating	Bonding, Fiber coupling	Quality control, Fundamental studies, Lifetime testing







Markets & applications of O-band QD lasers and SOAs

INNOLUME

Cloud Networking
- High power DFB for DR8 TRx
- CWDM single lasers and arrays
- Low Noise SOAs
- Gain chips for Coherent-Lite

AI/ML Clusters
- CW-WDM high-count channel DFB arrays
- Comb-lasers
- Ultra-Low Noise WDM SOAs

PON & MANs
- Ultra-Low Noise WDM SOAs
- BDFA MSA package

Fiber Sensors
- Narrow-line, widely tunable laser
- Intelligent drivers & interrogation systems

Terrestrial FSO
- Narrow line and high power DFBs
- High power SOAs

FMCW LiDARs
- Narrow line and high power DFBs
- High power SOAs
- Comb-Lasers
- FM lasers with constant P_{output}

Wireless Charging
- High power DFB and FP lasers

Travel through fiber — *Travel through air*

DFB lasers and laser arrays

- **300mW @ 85°C, 250mW @ 105°C, PCE 20%, in CW regime**
  Single DFB laser for DR4 and DR8 OT; External Light Source for CPO
- **Linewidth: <100kHz**
- **High yield DFB arrays: CW-WDM, CWDM single chip**
  Due to no single overgrowth step
- **No optical isolator needed**

Comb-laser

- **8 to 64 lines, 3 mW per lane, PCE >20% Grid 25-100 GHz,**
  solution AI driven connectivity

Comb-SOA

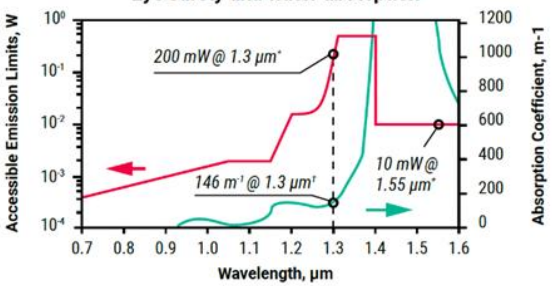
- **NF < 4db and Multi-lanes amplification, without modes interaction,**
- **High PCE up to 10%**

BDFA MSA package

- **analog of EDFA in O-band**
- **enabled by 1.19µm QD laser**
  700mW, PCE 40%

Non-tapered single-mode BOA

- **M^2 close to 1**
- **CW 1.5W @ 50°C, PCE 20%**
- **CW 0.8W @ 100°C, PCE 15%**

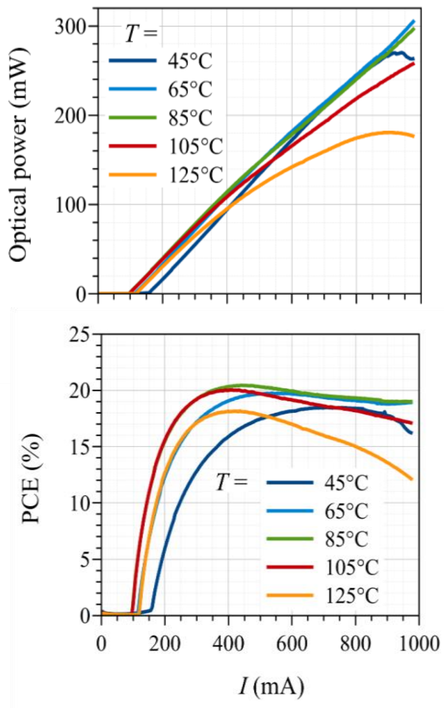


*IES 60825-1 2014-05 †Deng, R., et. al., 2012. Yaogan Xuebao-Journal of Remote Sensing, 16(1), pp.192-206.

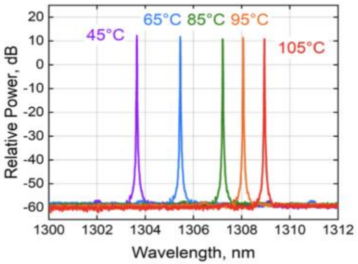
O-band High Power InAs/GaAs QD DFB laser

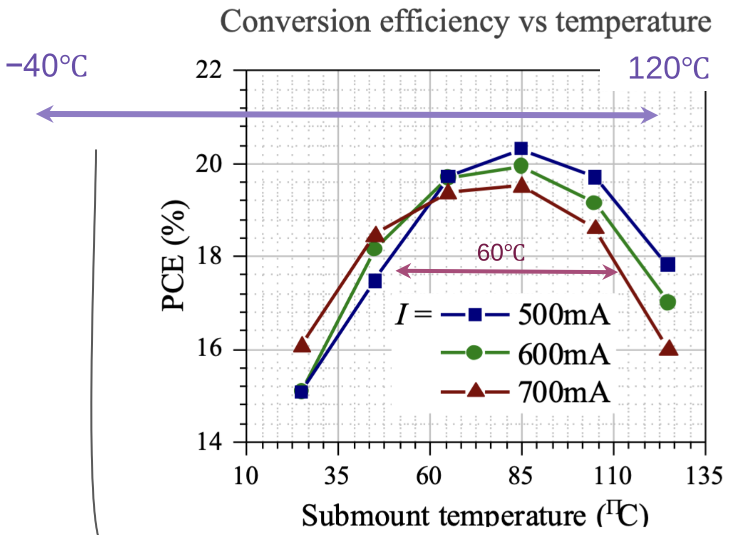
Optimized for high temperature operation

Optimized for 85℃



SMSR >55dB
RIN <150dB/Hz
Beam div: 35x7 deg



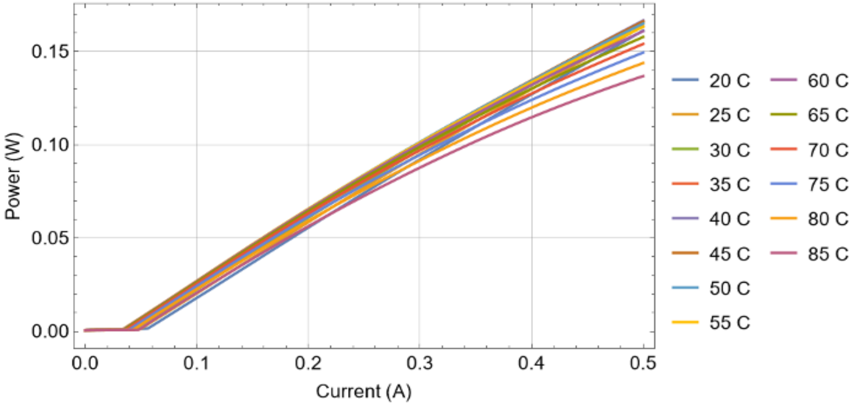


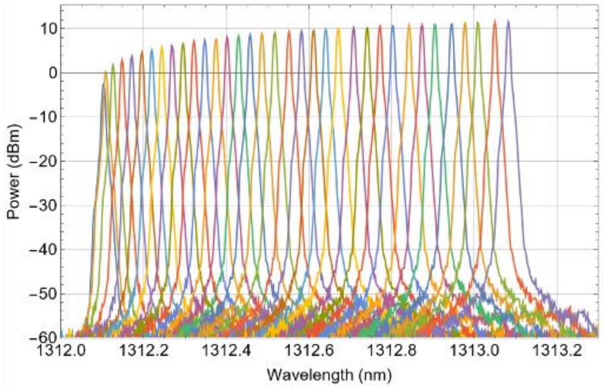
- Broader gain DFB lasers for the efficient operation in a wider interval of temperatures under development for various applications

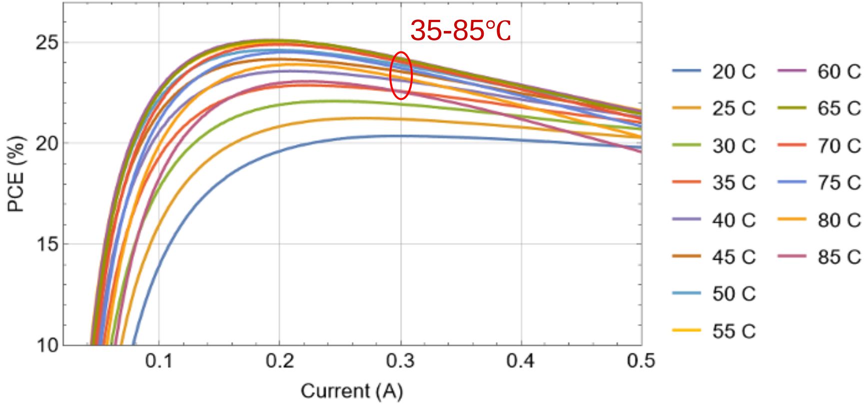
Matching the operation temperature of O-band photonics to the highest operating temperature of CMOS electronics

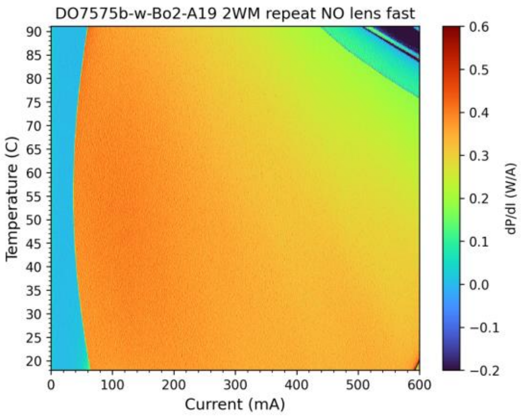
100mW CW DFB

HVM is being ramped up



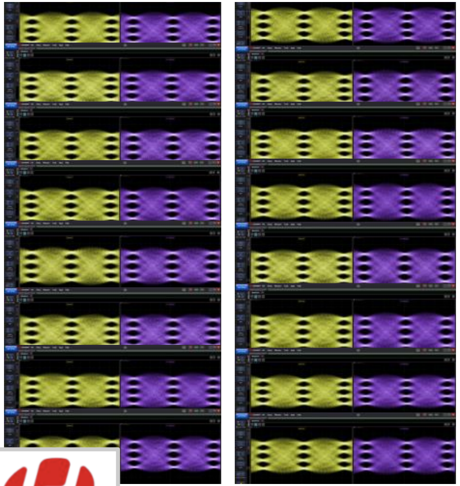




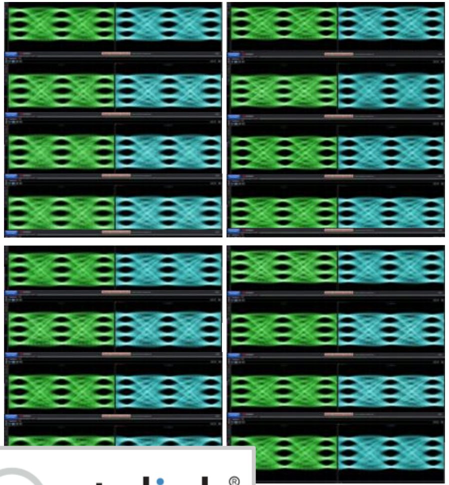


Demo at OFC2024 800G OSFP LPO DR8

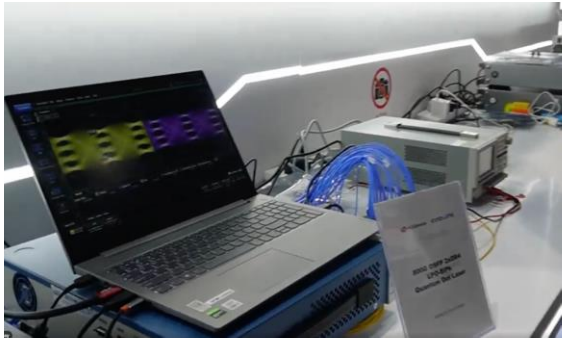
Case Temp 40℃



70℃



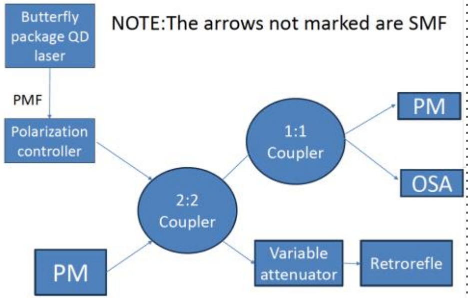
- 2 QD CW DFB lasers for 8 channels instead of 4 QW CW DFB
- SiP MZM
- No Optical Isolator
- Good eyes at TP2 point at both room temperature and 70C with < 2 dB TDECQ,
- 8W @ 70C

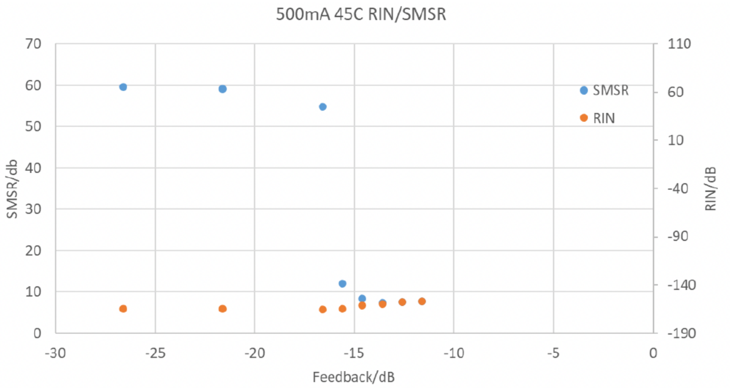


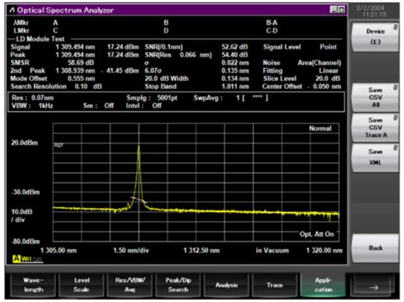
https://www.linkedin.com/posts/josepozophotonics_from-plan-to-commercial-reality-thanks-to-activity-7179167917169664000-8z5F?utm_source=share&utm_medium=member_ios

QD DFB laser sensitivity

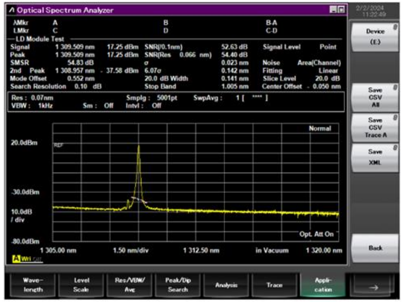
QD laser RIN/SMSR



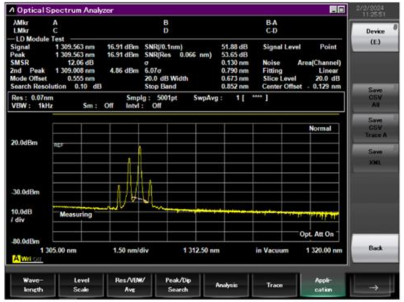




500mA 45C Feedback=-22dB

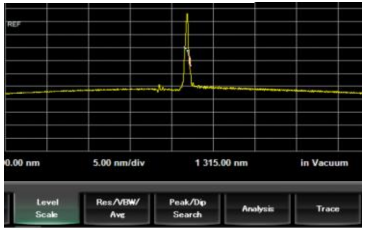


500mA 45C Feedback=-17dB

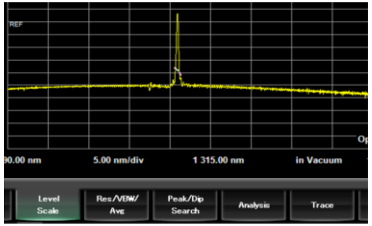


500mA 45C Feedback=-16dB

QW laser RIN/SMSR



500mA 45C Feedback=-22dB



400mA 25C Feedback=-31dB

- QD about 10 time more resilient to reflection back compared to QW
- Different mechanisms limiting the stability vs reflection back for QDs and QWs

Isolator-free data transmission using a feedback tolerant heterogenous III-V/Si quantum dot laser

Xinru Wu[1,*], Duanni Huang[1], Guan-Lin Su[1], Songtao Liu[1], Shane Yerkes[2], Harel Frish[2], Haisheng Rong[1]

1. *Intel Corporation, 2200 Mission College Blvd, Santa Clara, CA 95054*
2. *Intel Corporation, 1600 Rio Rancho Blvd SE, Rio Rancho, NM87124*

**xinru.wu@intel.com*

Abstract: We demonstrate an isolator-free 128 Gb/s PAM4 data transmission using a silicon microring modulator and a heterogeneous III-V/Si quantum dot laser in the presence of optical feedback of up to -13dB. © 2024 The Author(s)

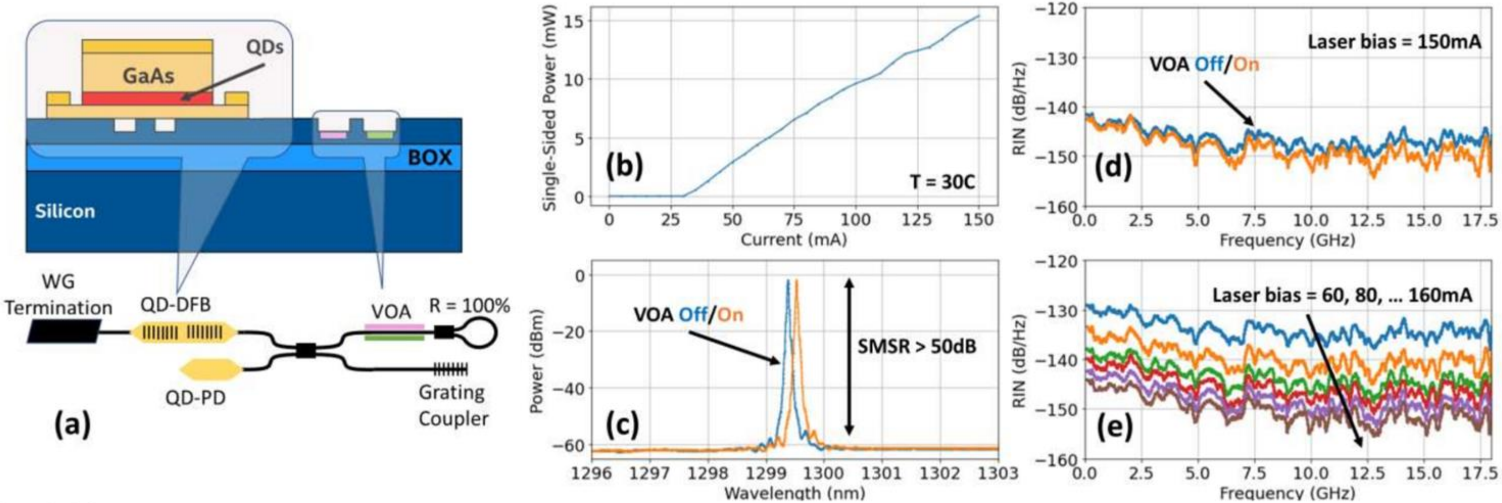
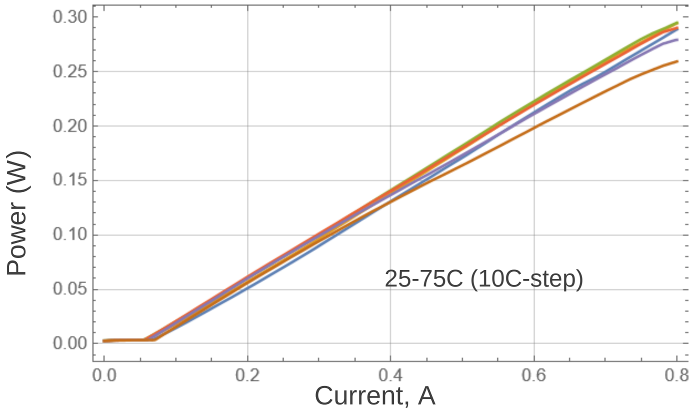
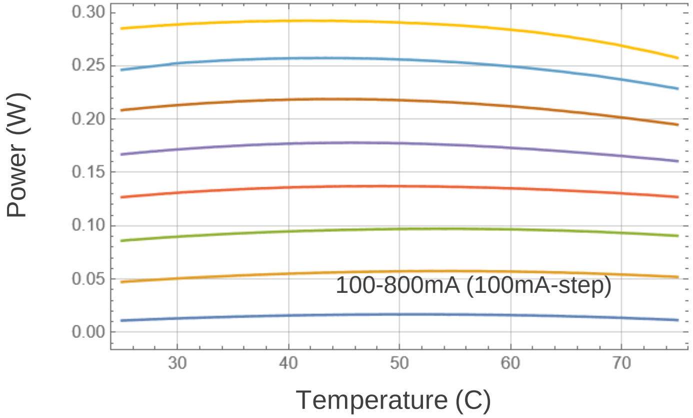
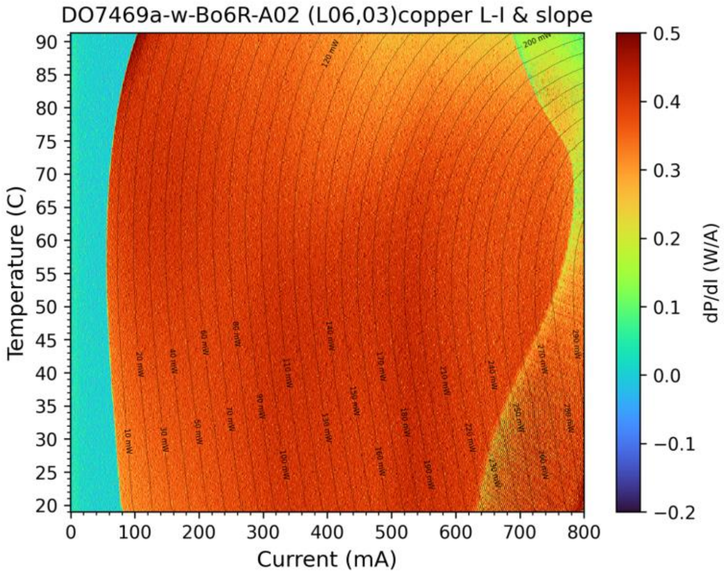


Fig. 1 (a) Schematic of the heterogeneous silicon QD-DFB laser with on-chip optical feedback control; (b) L-I curve of the QD-DFB; (c, d) Measured optical spectrum and RIN with (reflection = -30dB) and without (reflection = -13dB) VOA attenuation. The slight shift in lasing wavelength is due to the thermal crosstalk between the VOA and laser. (e) RIN of the QD-DFB at various bias currents, measured with VOA off.

300 mW DFB for ELS

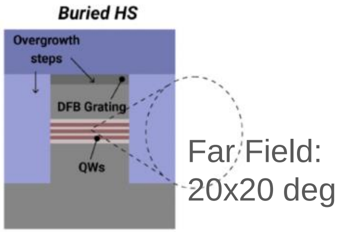


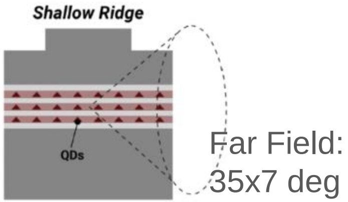


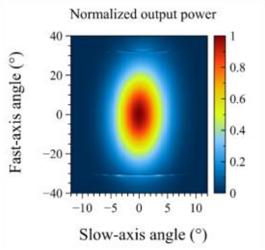


High Power 1.3 µm GaAs arrays

GaAs vs InP	InP QW BHS High Power DFB	GaAs QD High Power DFB
Wafer process	Complicated due to two overgrowth steps	Simple, Shallow mesa
Die Yield	Below 90%, due to overgrowth	High, to be proven in volume production fashion
Manufacturability	Much worse than Silicon	Worse than Silicon
Wafer Size	3-4 inch, expensive	4-6 inch, low cost
Reliability	Better than VCSELs	Expected to be superior
Ease of coupling	Optical Isolator is needed	No need in OI
High temperature	PCE steeply falls above 80°C	PCE can be as high as 20% at 100°C







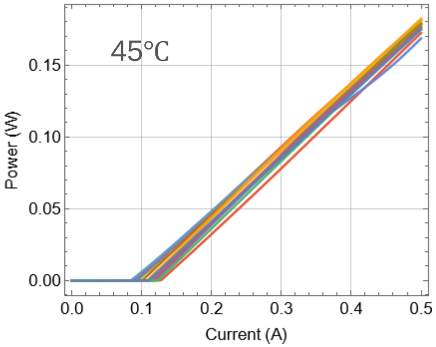
DFB laser arrays - very first results

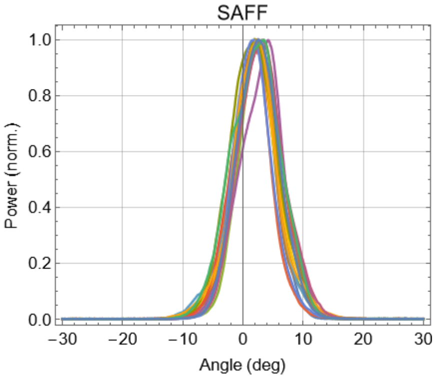
3x2 mm

HR

AR

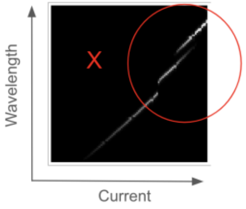
16 DFBs, pitch 125um

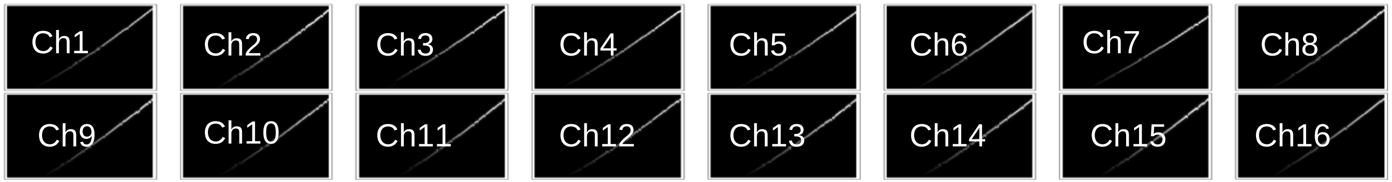




Optical power (current, wavelength)

Example for a bad laser



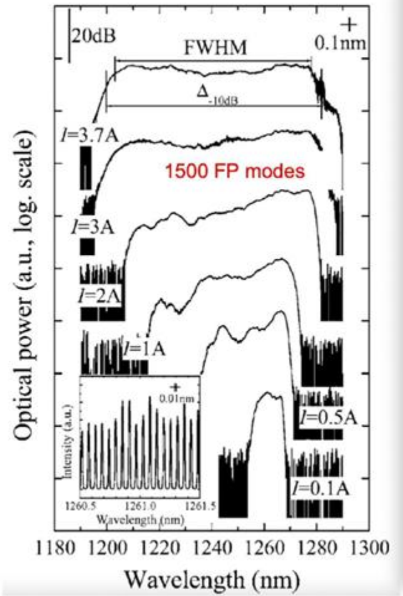


Second wind of QD comb lasers

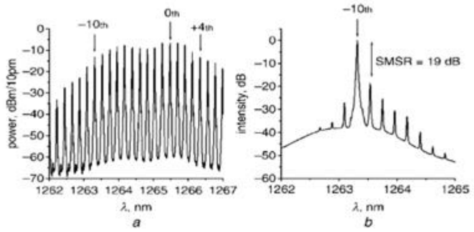
INNOLUME

17 years ago:

Quantum dot laser with
75 nm broad spectrum of emission //
A.Kovsh et. al., Optics Letters, April 2007



FP modes of low-noise quantum dot laser //
A.Gubenko et. al., Electronics Letters,
December 2007



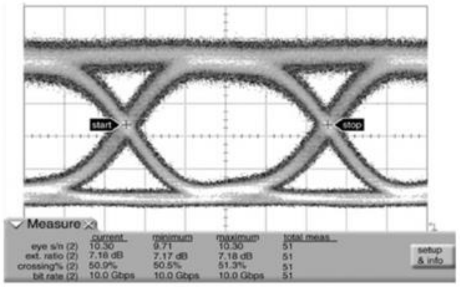
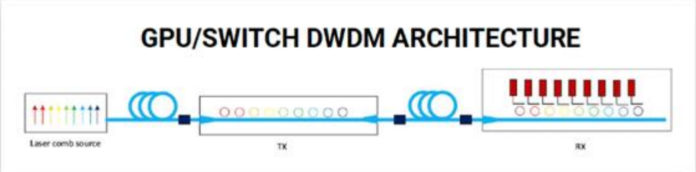


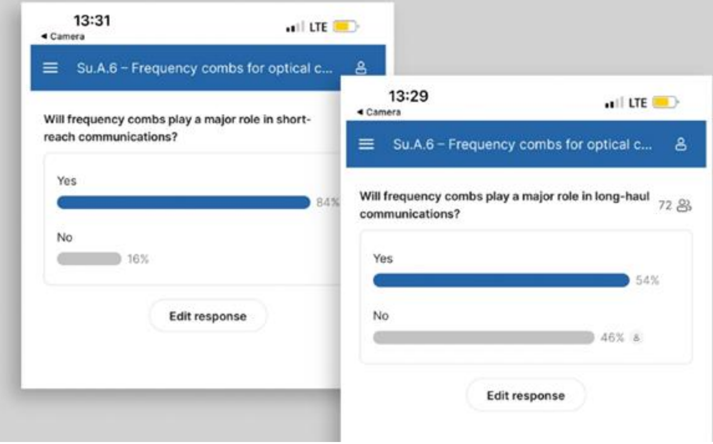
Fig. 3 *Eye diagram generated by 10 Gbit/s digital modulation for one of ten filtered longitudinal modes for which BER < 10^{-13} was measured*

Today:

OFC March 6, 2023:
Optical Communication for Data Centers and HPC // Bill Dally, SVP, NVIDIA



ECOC 2023 Survey:
Frequency Comb for Optical Communications – Hype or Hope?

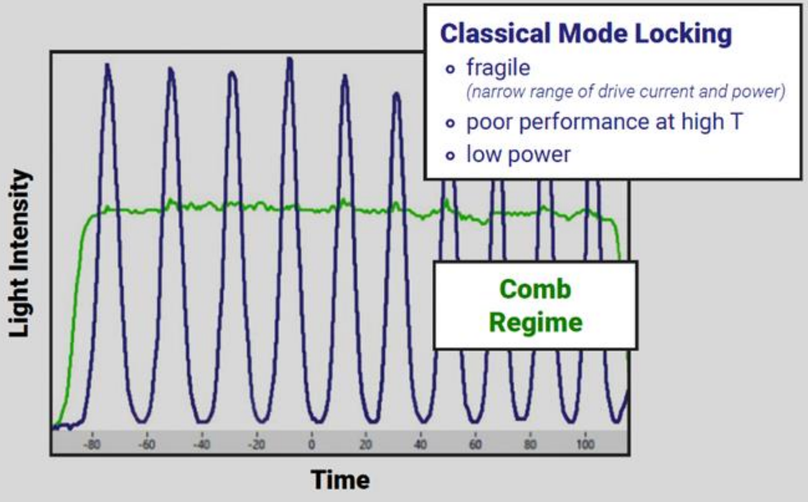


QD comb laser: New type of Mode-Locked diode lasers

INNOLUME

Difference with classical Mode-Locked lasers

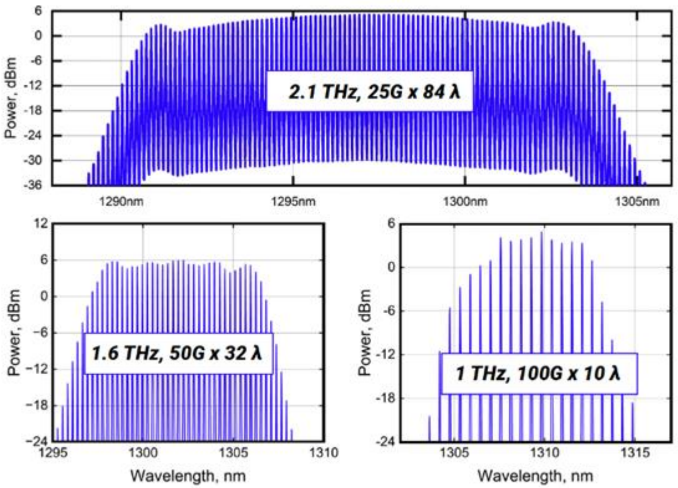
- Stable operation (wide spectrum locked and low RIN) in a wide range of drive current and temperature
- Total power is stable with time — no total intensity pulses
- Mode locking occurs even without saturable absorber



Invented by Innolume in 2007

Current level of performance

- **Number of modes and spacing:**
  64 x 25 GHz   32 x 50 GHz   12 x 100 GHz
  16 x 100 GHz under development
- **Total CW Power up to 250 mW with PCE 25%**
- **Efficient operation up to 100ºC**



INNOLUME

Laser Reliability is the key

Vacuum Tube Computer, **70 years ago**

Could not finish the calculation before some **vacuum tube fails**

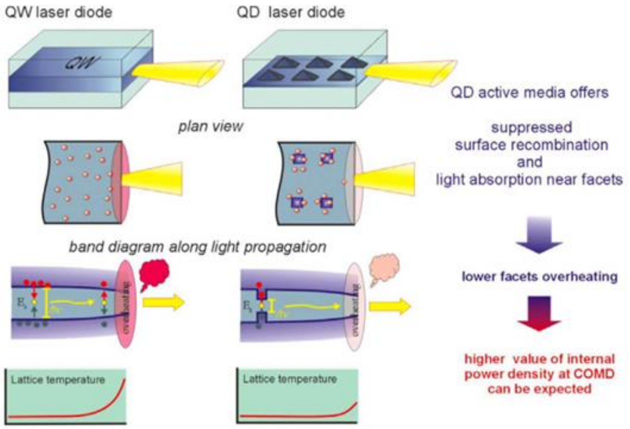
NVIDIA supercomputer, **today**

Can not finish the model training before some **laser fails**

Laser Failure is a Root Cause for more than 85% of Optical Modules hardware failures in Cloud Networks

FUNDAMENTALLY BETTER RELIABILITY // 3D ISLANDS OF RELIABILITY

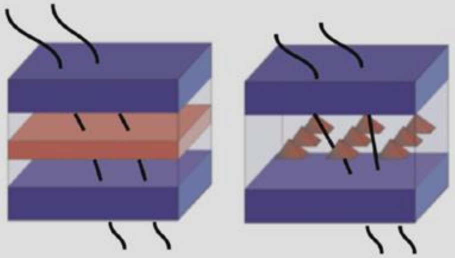
In-situ ***window structure*** prevents Catastrophic Optical Mirror Damage (COMD)



We have never observed COMD in QD lasers

Reduced effect of threading dislocation on threshold current and differential efficiency

100-1000x RAD Hardness



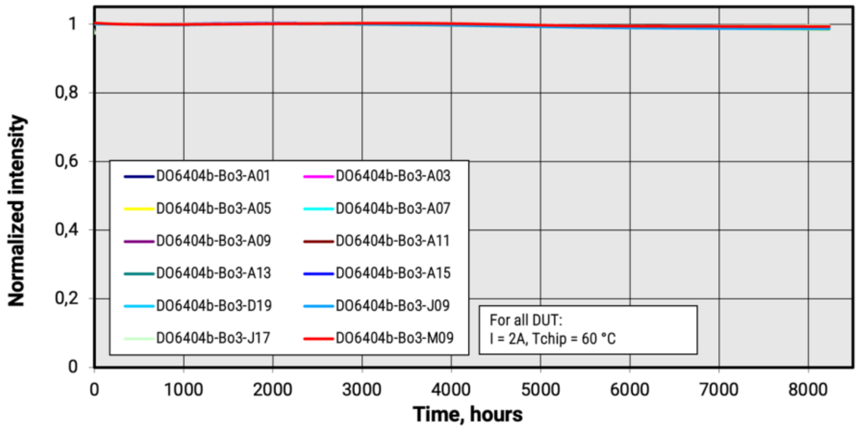
Quantum well (left) and dots (right) structures with threading dislocations (black lines)

We have never observed sudden failure in QD lasers

Preliminary Life-Time Studies

Our Data

FP Single Mode, CW Power: **900mW / 10MW/cm²**



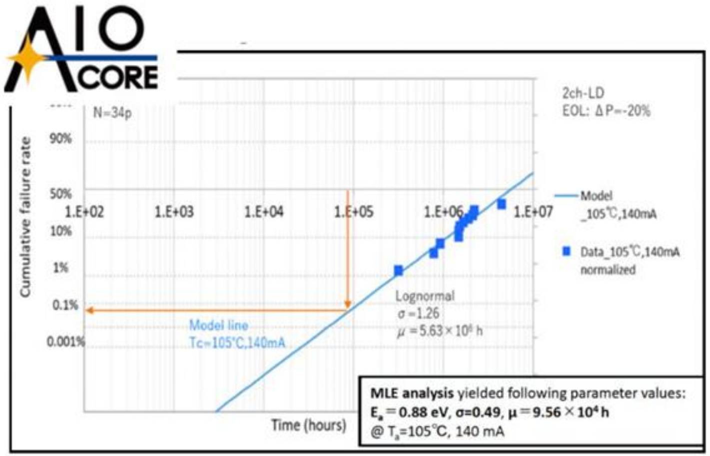
Test:
I=2A, Pout=900mW, T=60C

Ea= 0.43eV
Power acc. constant =3
Current acc. constant =2

LT estimate @T=25C,
P=900mW
380 khours / **50 years**

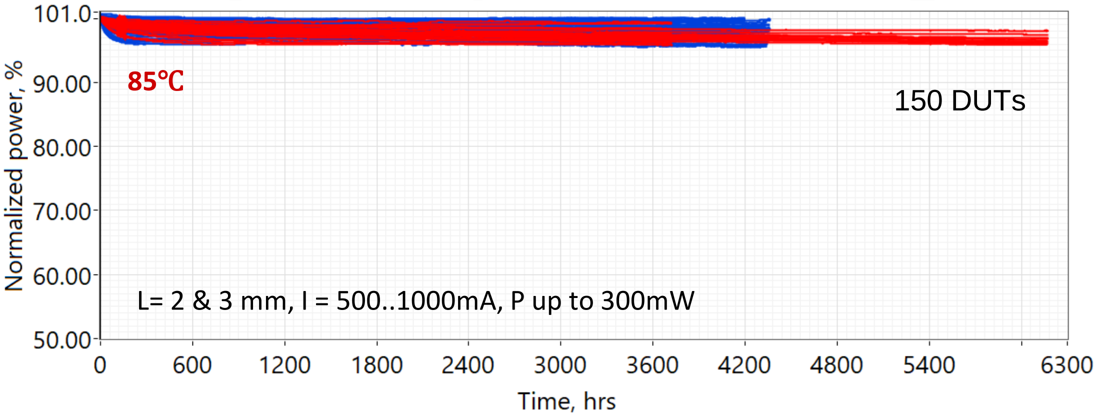
Customer Data: AIO Core, Japan

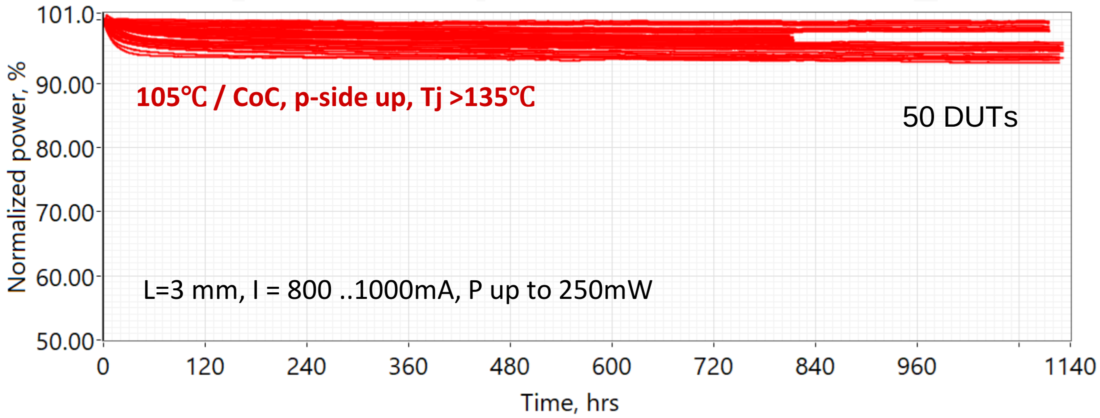
FP Single Mode, CW Power: **50mW**



Tc, °C	Cumulative failure rate	Average FIT
85	*< 0.001%*	*0.1*
105	*0.049%*	*5.6*

On going ALT of DFB at 85℃ and 105℃





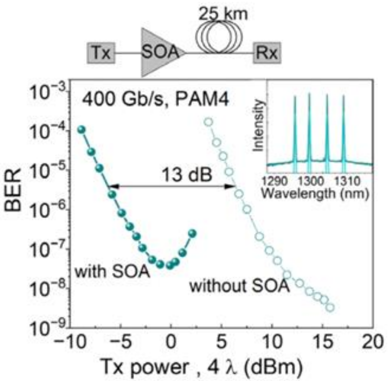
- Through the lifetime of Innolume there was no single sudden failure of QD laser was observed (thousands of burned-in lasers), whereas it happens for Innolume QW
- There was no single RMA for the modules produced by Innolume using QD lasers (thousands of module shipped), whereas it happened for the modules based on QWs
- The collected internal data are not yet enough to extrapolated FIT related to manufacturing process
- The expected lifetime 200mW @85C exceeds 7 years

Semiconductor analogue of EDFA

INNOLUME

QD Semiconductor Optical Amplifier (SOA) operates in 2 regimes:

1. WDM data transmission

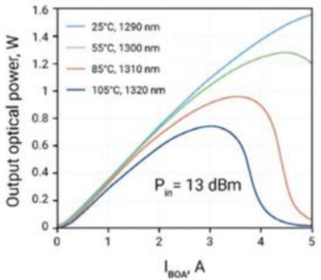


Performance

- P_{out} = 2 mW per channel
- Noise figure: 4 dB (not including fiber CE)
- Power budget improvement: 13 dB
- Error-free data transmission for NRZ

2. High-saturation power

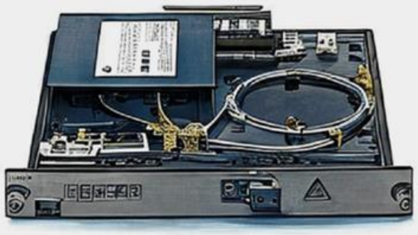
Utilized for FSO LiDARs and Terrestrial FSO



Performance

- P_{out} up to 1.5 W
- P_{sat} up 26 dBm
- Temperature up to 105 °C
- PCE up to 28%
- Single mode, no astigmatism

Conventional EDFA

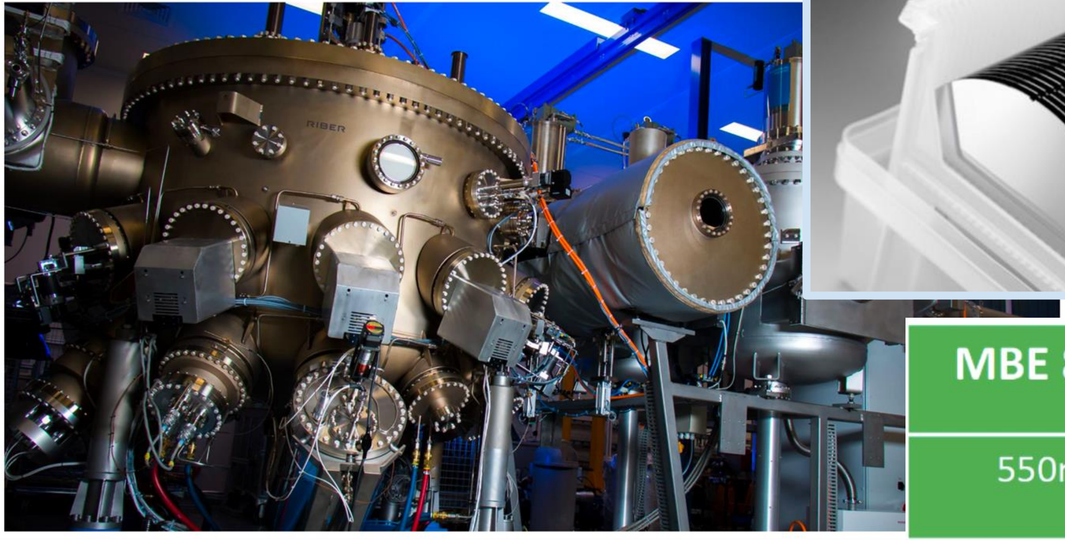


Our SOA

Innolume's low-noise WDM SOA is optimized for signal amplification in state-of-the-art data transmission links. Thanks to its low noise figure and the highest saturation power on the market, the WDM SOA can be used across a wide range of input powers with minimal effect on bit error rate.

GaAs economics

MBE 8000 – multi-4”, 6” and 8” wafers



MBE 8000
550mm
1x450mm 4x8” 8x6” 14x4”

2023 6-inch equivalent GaAs
wafer consumption is **3kk pts**
LEDs, RF, VCSELs, EELs

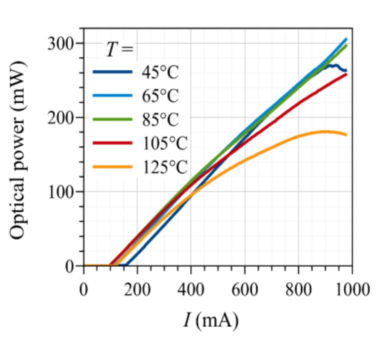
Unique features of GaAs QD-based devices to serve SiPh

- **Efficient operation up to 120°C**
- **Fundamentally better reliability**
  in-situ "window structure" and much lower sensitivity to the dislocations
- **Much better manufacturability of GaAs vs InP on top of simpler DFB laser process**

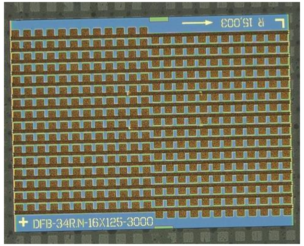
- **Lower α-factor and feedback sensitivity**
  no Optical Isolator needed
- **Single-chip WDM capability**
  High yield DFB & SOA arrays,
  Comb lasers,
  External Cavity combs with gain chips & μ-rings,
  Ultra-low noise Comb-SOA

Ease of Integration with SiPh and emerging modulation technologies (TFLN, BTO/Si, Organic)

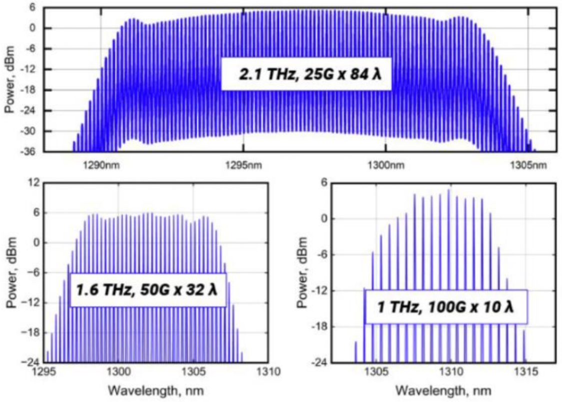
DFB @120℃



DFB arrays x8, x16



QD Comb lasers



Ultra-low Noise Comb-SOA

Recent development