Status of silicon photonics reliability test

Ichiro Ogura, PETRA
Richard Pitwon, AIO Core

IEEE 802.3cz Multigigabit Optical Automotive Ethernet Interim Task Force

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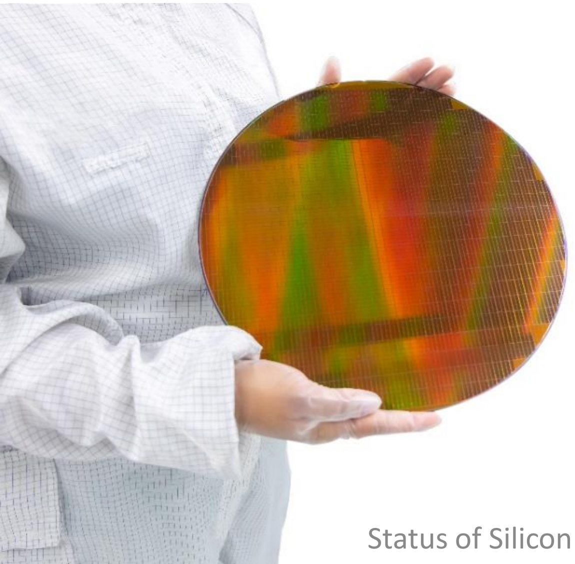
Clarifying misconceptions around silicon photonics

1310 nm is the dominant wavelength for current and future data centre Ethernet standards and will drive communication laser demand

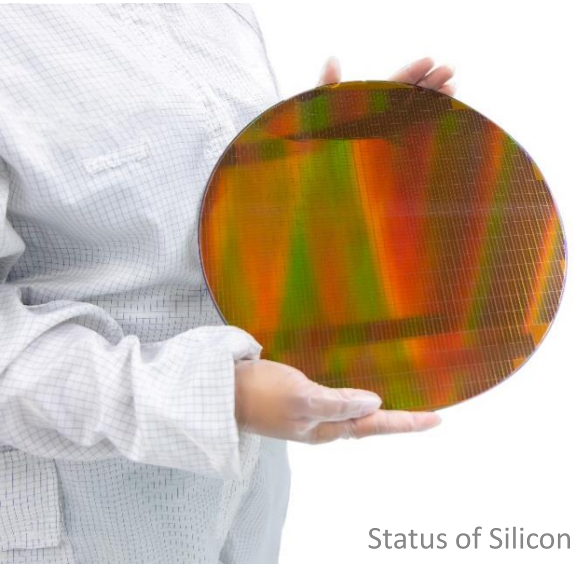
Speed	Ethernet Nomenclature	Lane no x Nominal rate	Link distance / medium	Wavelength	Standards group
100 GbE	100GBASE-SR10	10 x 10G NRZ	150m OM4 10 pair MMF	850 m	802.3ba
	100GBASE-SR4	4 x 25G NRZ	100m OM4 4 pair MMF	850 nm	802.3bm
	100G-PSM4		500m on 4 pair SMF	**1310 nm**	MSA
	100G-CWDM4		2km on duplex SMF	**CWDM (1271nm, 1291nm, 1311nm, 1331nm)**	MSA
	100GBASE LR4		10 km on duplex SMF	**LAN-WDM (1295 nm, 1300 nm, 1305nm, 1310 nm)**	802.3ba
200 GbE	200 GBASE-SR4	4 x 50G PAM4	100m on 4 pair OMF MMF	850 nm	802.3cd
	200 GBASE-DR4		500m on 4 pair parallel SMF	**1310 nm**	802.3cd
	200 GBASE-FR4		2km on duplex SMF	**CWDM (1271nm, 1291nm, 1311nm, 1331nm)**	802.3cd
	200 GBASE-LR4		10 km on duplex SMF	**LAN-WDM (1295 nm, 1300 nm, 1305nm, 1310 nm)**	802.3cd
400 GbE	400 GBASE-SR16	16 x 25G	100m on 16+16 parallel OM4 MMF	850 nm	802.3bs
	400 GBASE-FR8	8 x 50G PAM4	2km on duplex SMF	**4.36 nm WDM grid over 1310 nm**	802.3bs
	400 GBASE-LR8		10km on duplex SMF	**4.36 nm WDM grid over 1310 nm**	802.3bs
	400GBASE-DR4	4 x 100G PAM4	500m on 4 pair parallel SMF	**1310 nm**	802.3bs



Clarifying misconceptions around silicon photonics

Industry support

Multiple MSAs around silicon photonics including:
PSM4, CWDM4, 100GLambda, CW WDM



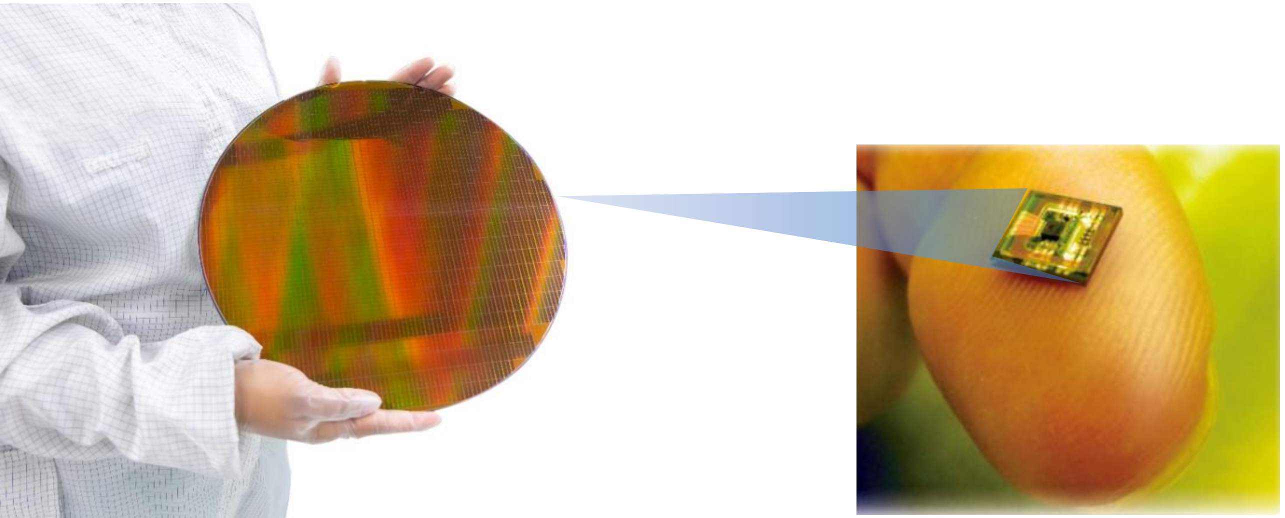
Mainstream international foundries manufacture silicon photonics

- Global Foundries
- TSMC
- ST Microelectronics
- Intel
- TowerJazz
- VTT
- Skorpios
- iHP
- CompoundTek
- Silex
- AIM Photonics
- APM
- CEA Leti
- IMEC
- AMF
- Skywater

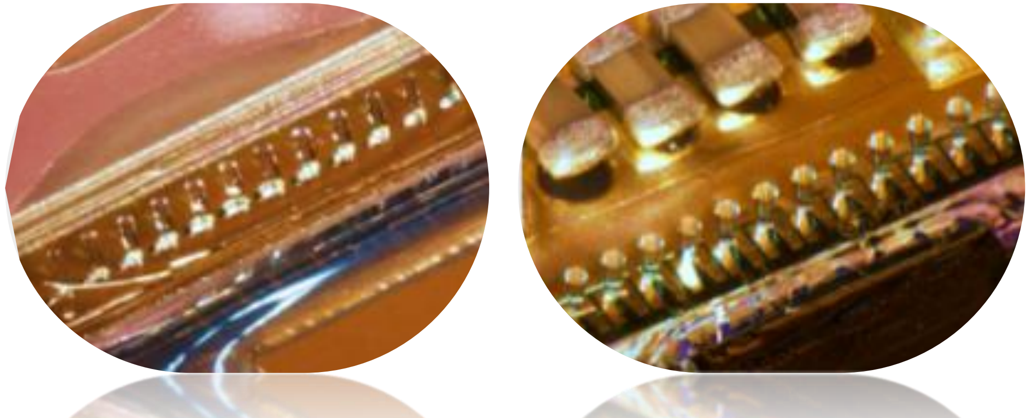
Clarifying misconceptions around silicon photonics

Cost depends on volume, chip size and assembly

- Silicon photonics benefits from mature CMOS process
- The cost of silicon photonics is determined by chip size. A 1-ch silicon photonics transceiver would be almost equal to a transceiver and receiver IC
- Coupling to GI-MMF (OM3) requires very low-cost passive alignment.



Multimode interface



Clarifying misconceptions around silicon photonics

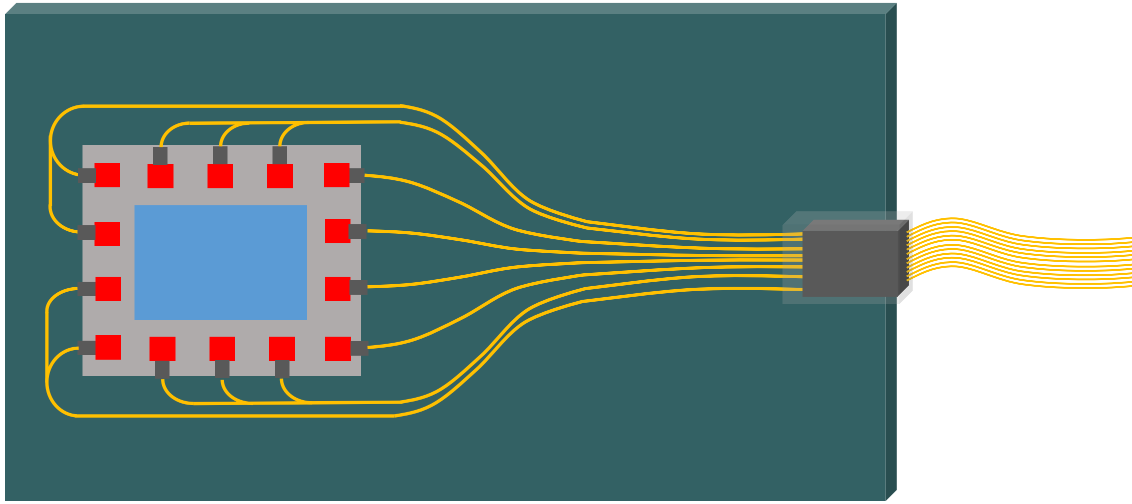
- There is a wide spectrum of silicon photonics transceivers targeting different applications and cost sensitivities.

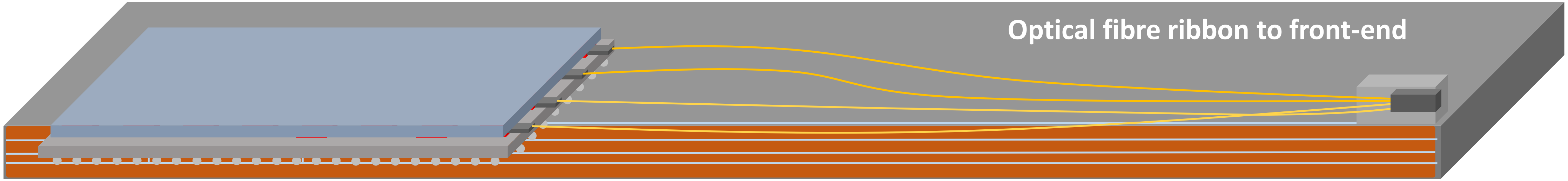
- **High-end silicon photonics for telecommunications**
  - At the high-margin telecommunications end, advanced silicon photonics based transceivers incorporating coherent, DWDM, PQSK and other advanced features are expensive. These are the devices traditionally associated with silicon photonics.
- **Competitive silicon photonics transceivers for data centres**
  - For the past 6 years, front-pluggable transceivers such as QSFPs and AOCs based on silicon photonics have been commercially available for wide-spread deployment in data centres competing with VCSEL based devices. The data centre is a highly cost-sensitive environment and purchase decisions are based primarily on cost.
- **Co-packaged optics driving low relative cost silicon photonics**
  - For the next 5 years, co-packaged optics will continue to drive silicon photonics costs further down and reliability further up.

Co-packaged optics (CPO) is driving silicon photonics evolution

Over the next few years the need for co-packaged optics (CPO) solutions will drive costs further down and reliability further up in a higher temperature environment than has been typical of data centres.

Silicon photonics is the only serious contender to meet this challenge.
VCSEL based CPO were also considered, however where CPO environments are now expected to exceed 100°C they are not considered viable given the high reliability requirements.





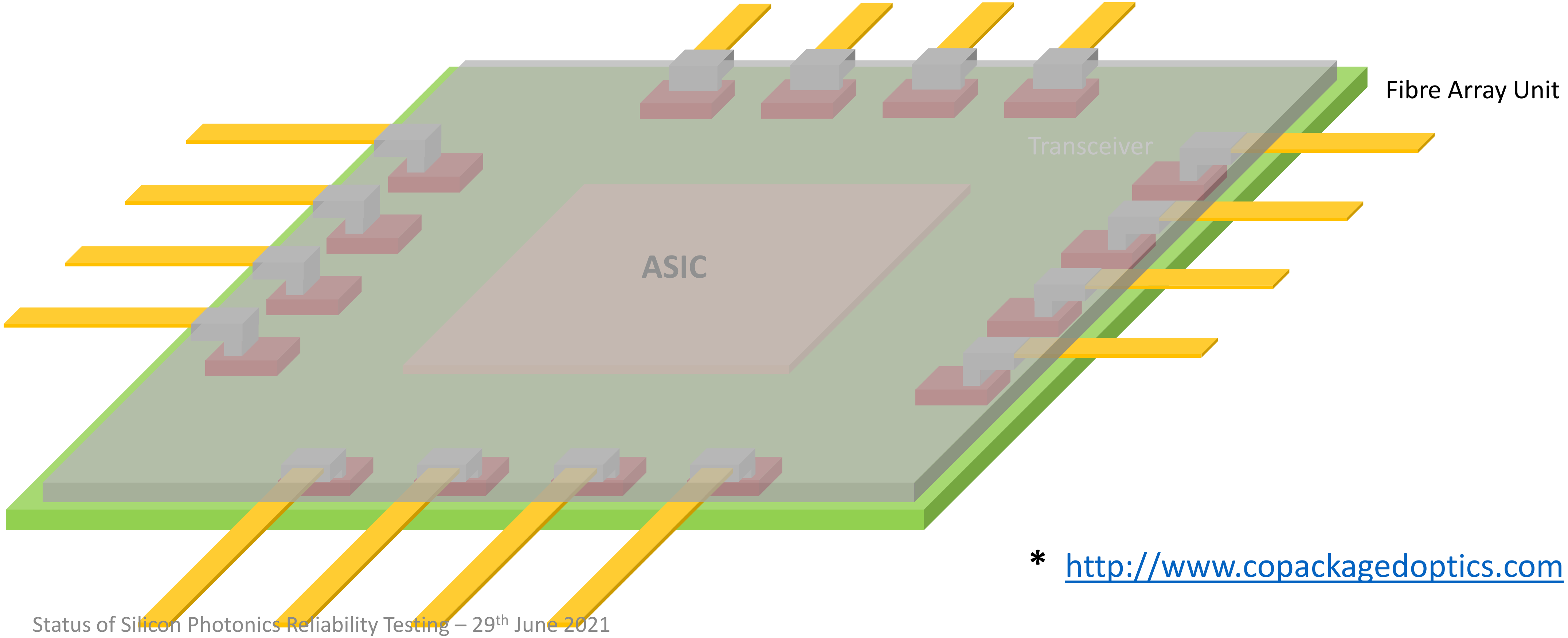
High speed electrical PCB trace length range < 1 cm

Co-packaged optics (CPO) is driving silicon photonics evolution

Co-Packaged Optics Collaboration *

Founded in March 2019 by Microsoft and Facebook

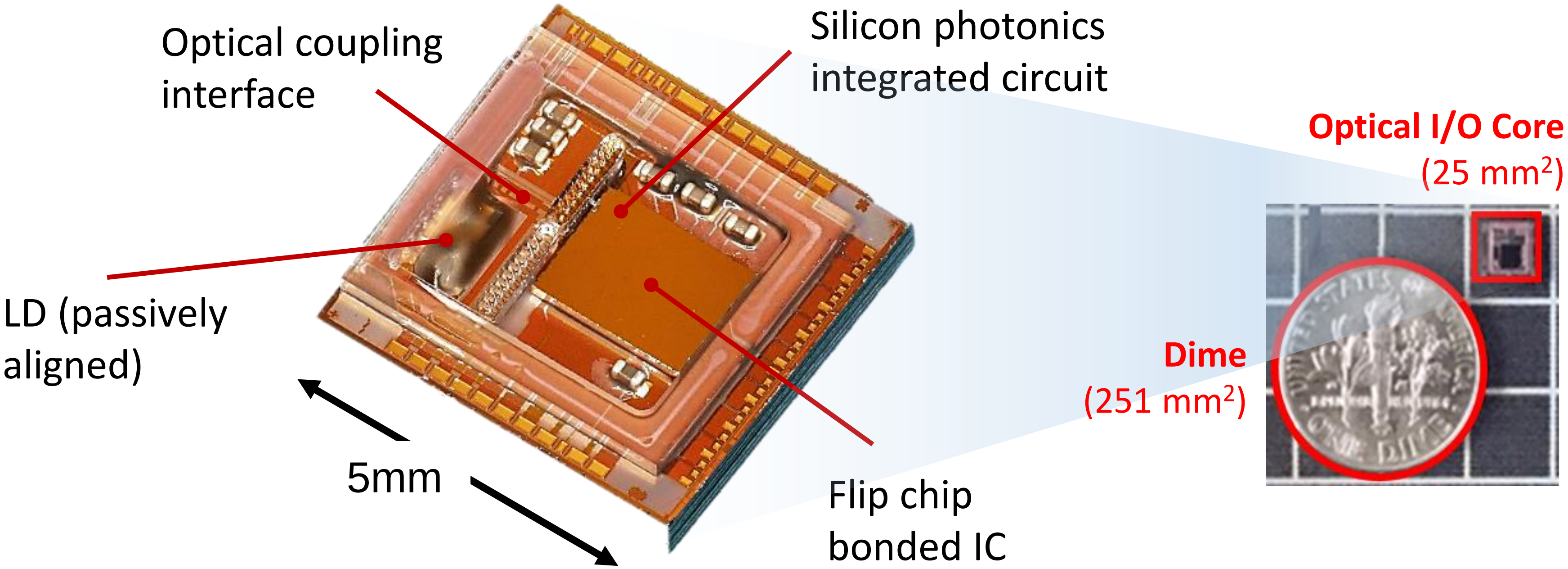
First specification for 3.2T CPO released in 2021



* http://www.copackagedoptics.com

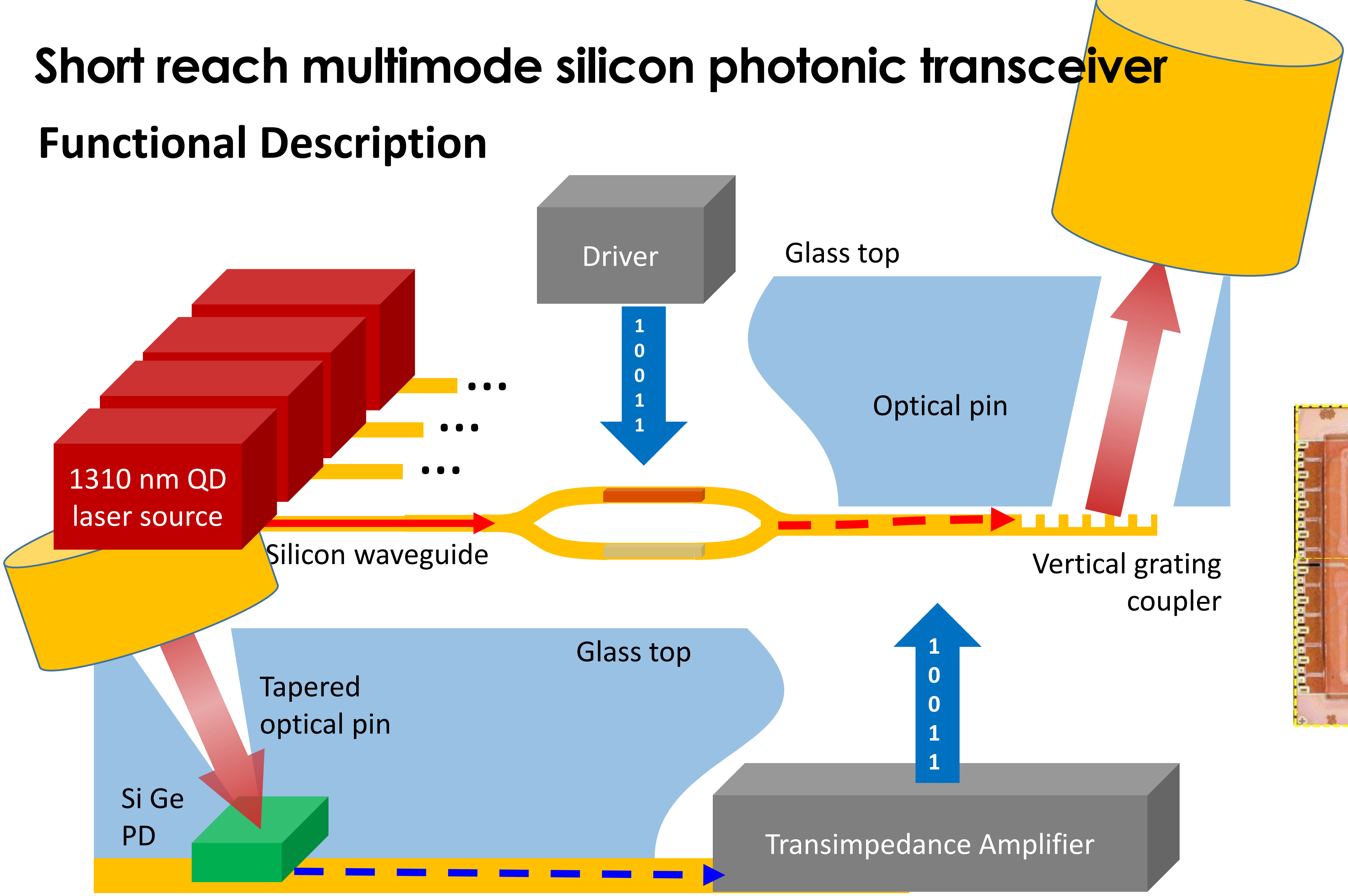
Example of competitive silicon photonics transceiver

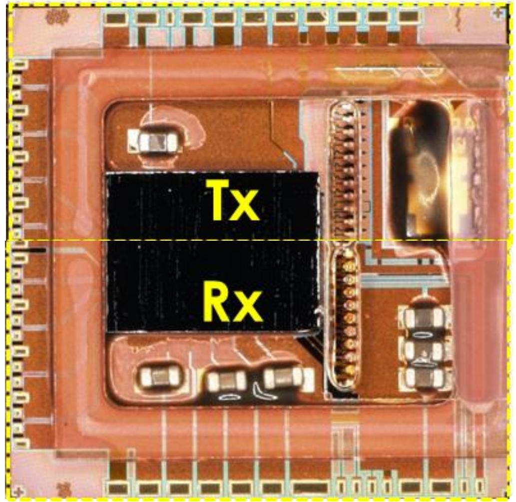
- This silicon photonics micro-transceiver design is simplified and accommodates a multimode fibre interface in order to minimise relative cost, targeting short-reach and high-temperature applications.
- Although this specific example would probably not be used for automotive, it serves as a testbed or demonstrator for how silicon photonics can be cost competitive.



Short reach multimode silicon photonic transceiver

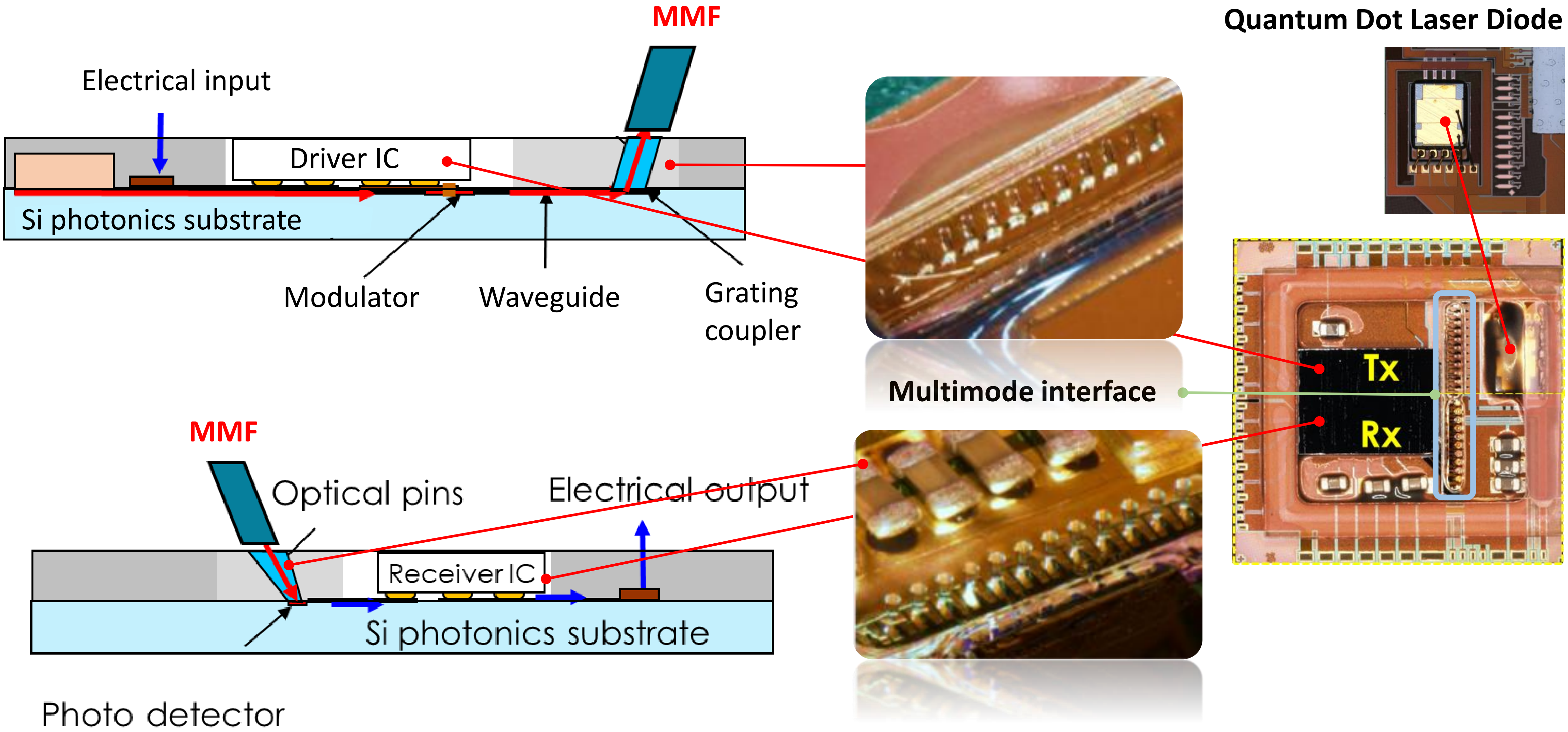
Functional Description





Short reach multimode silicon photonic transceiver

Component overview

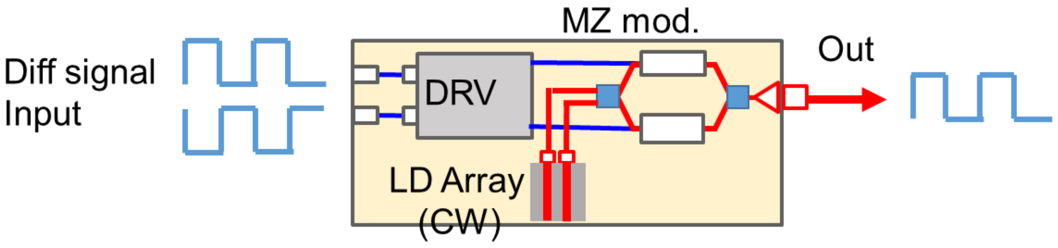


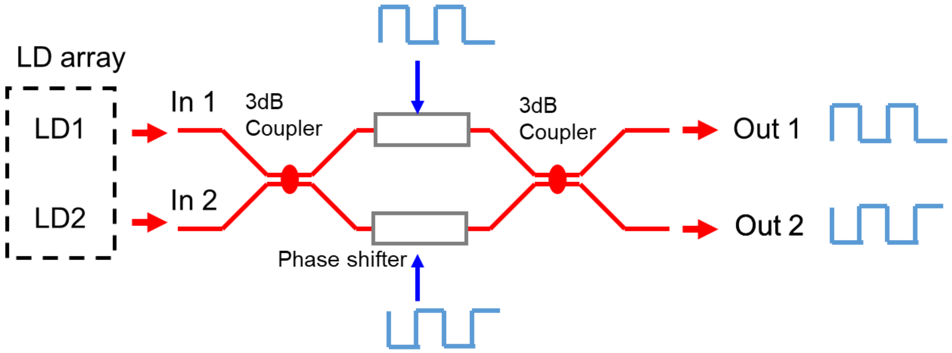
Redundant optical circuit for increased reliability

Built-in dual redundancy in Si photonics Transceiver

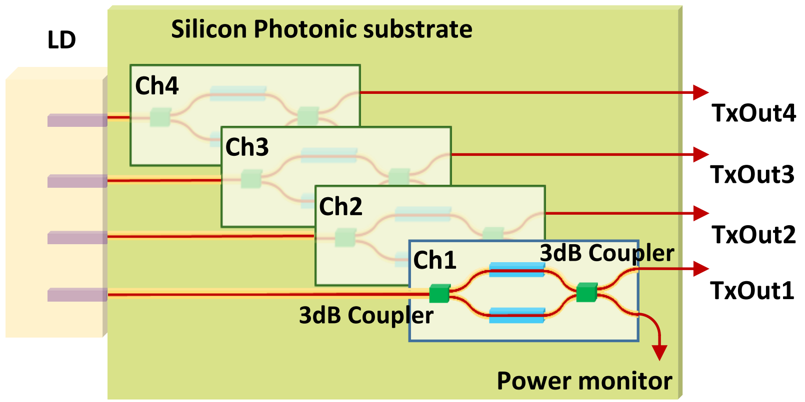
MZI-modulator configuration allows for dual light sources to be operated as redundancy

Redundant light sources integrated in Si Photonics chip

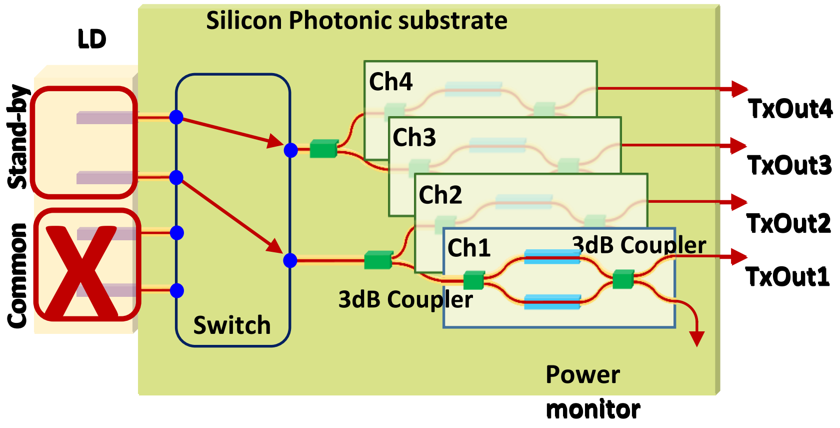




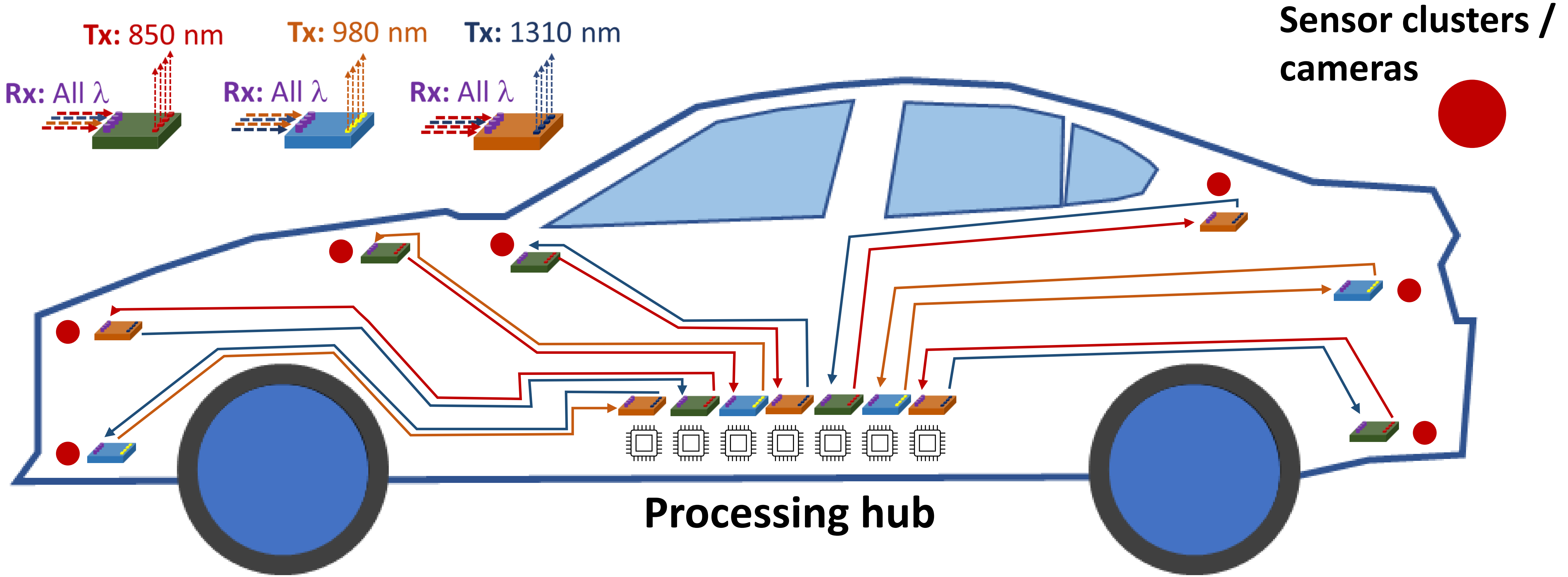
1) 1st generation QD-LD and MZ configuration



2) 2nd generation configuration with redundancy



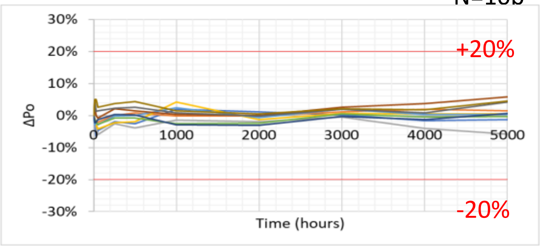
Internal optical communication in automotive applications



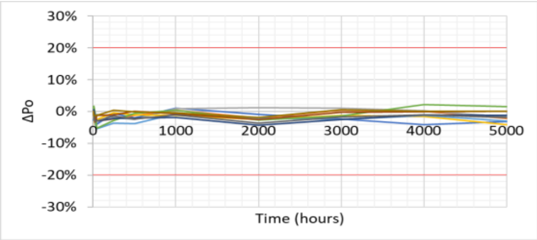
Reliability of optical communication links in automotive applications is critical and not to be compromised.

Ongoing reliability tests of Quantum Dot Laser Diodes (QD-LDs)

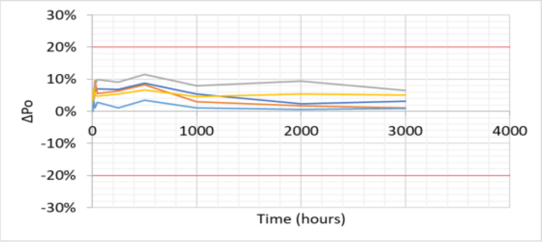
80°C,120mA/2ch (Tj=93.8°C) N=10p



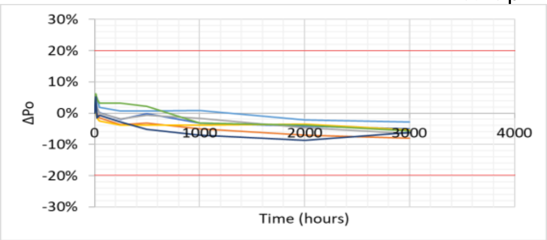
100°C,120mA/2ch（Tj=113.8°C） N=10p



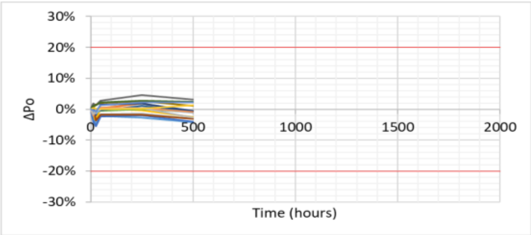
105°C,120mA/2ch（Tj=118.8°C） N=5p



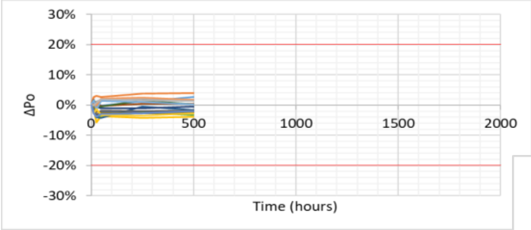
105°C,220mA/2ch（Tj=130.3°C） N=7p



100°C,300mA/2ch（Tj=134.5°C） N=17p



100°C,390mA/2ch（Tj=144.9°C） N=17p



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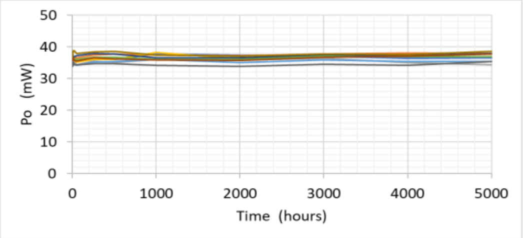

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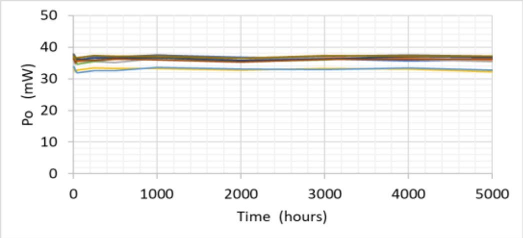

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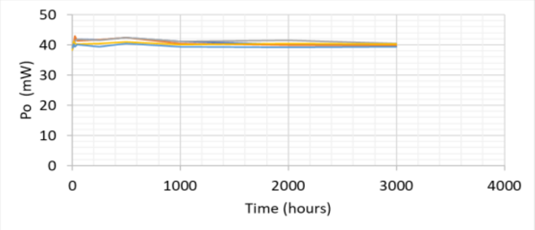

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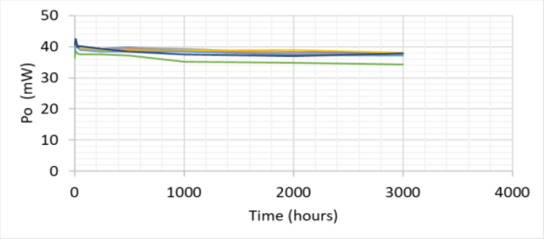

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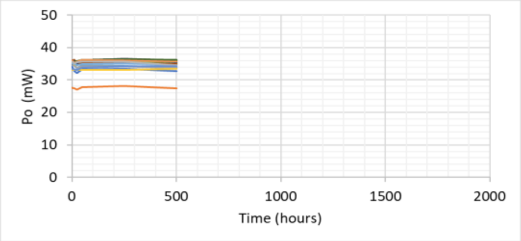

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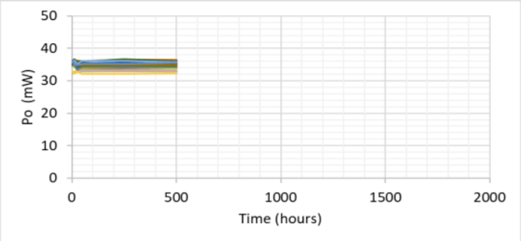
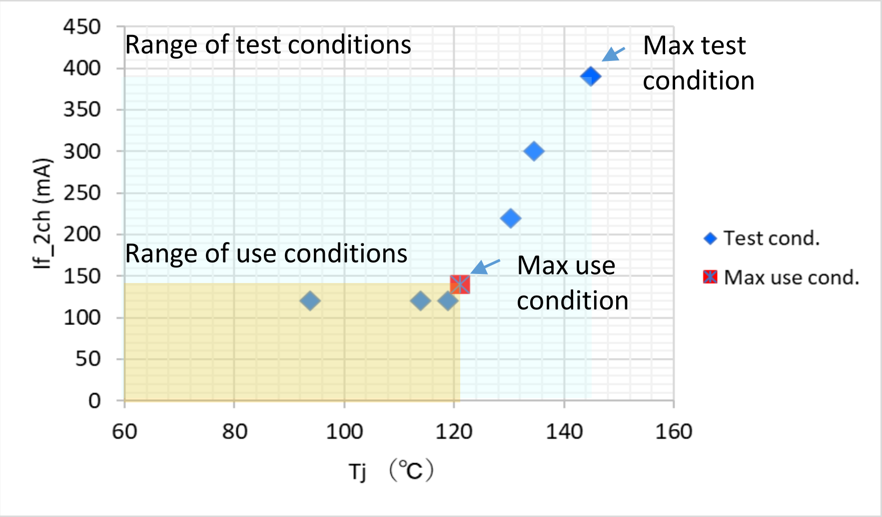


Test chip: Integrated 2ch-LD
Sample size: N=66 pieces (equivalent to 132 pieces of single-LD)
No sudden failures

Automotive mission profiles are well covered by test conditions.

If_2ch vs Tj Test and Use condition



ΔPo, Po were measured at 85°C,100mA

Wear-out failure estimates for QD-LDs

Method of estimating wear-out lifetime

- Estimate linearly extrapolated lifetimes (EOL) for -20% power drop
- Apply following reliability models:
  - Lognormal distribution
  - Acceleration factors : Junction temperature (Tj), Current (I)

Unreliability formula

$$F(t) = \Phi\left(\frac{\ln(t) - \ln(\mu)}{\sigma}\right)$$

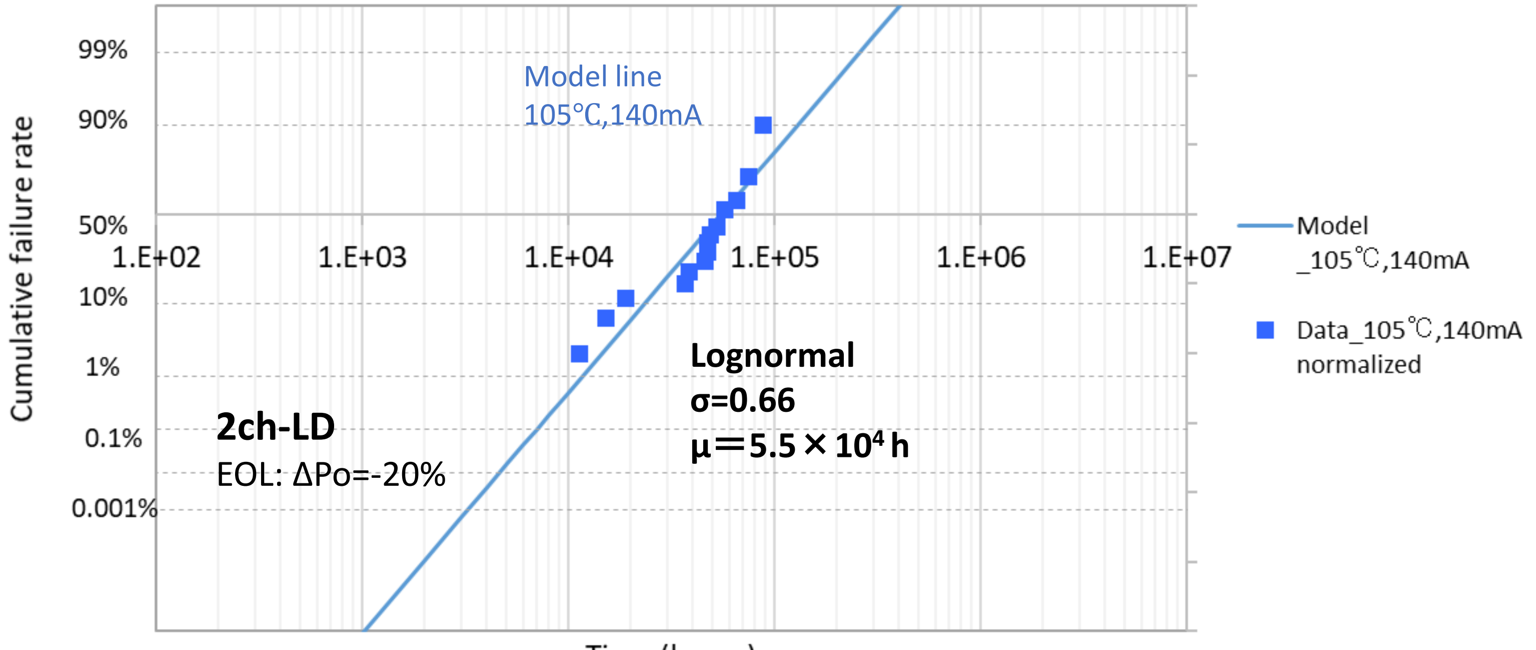
$$\mu = \mu_0 \cdot exp\left(\frac{E_a}{k_B \cdot Tj}\right) \cdot I^{-n}$$

F(t) : Unreliability function, **t** : Time
Φ : Standard normal distribution
Ea, n, σ, μ_o : Constants
k_B: Boltzmann constant

Maximum Likelihood Estimate (MLE) analysis was conducted using three test conditions, in which tests reached more than **3000 hours** and accurate lifetimes could be estimated.

MLE analysis yielded following parameter values:
E_a=0.97 eV, σ=0.66, μ=5.5×10^4 h @ T_a=105°C, 140 mA

Lognormal probability plot
(normalized to 105 °C, 140mA)
Sample N = **22p**

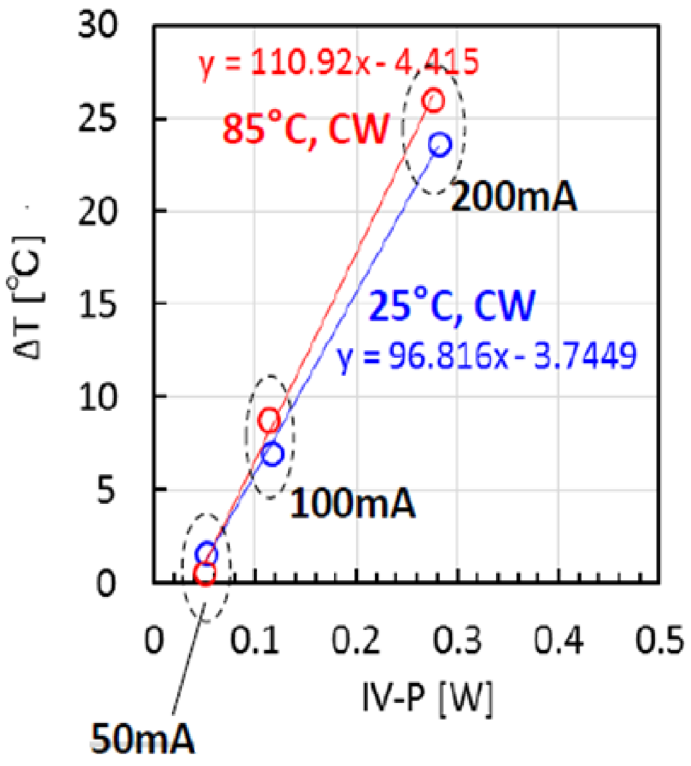


Projected MTTF values based on wear-out failures

2ch-LD EOL: ΔPo=-20%

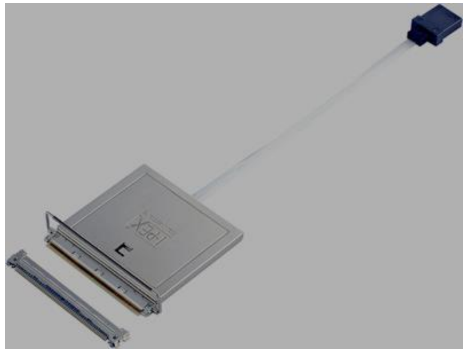
Ta (deg C)	If 2ch (mA)	Tj (deg C)	ML(=μ) 2ch (h)	MTTF 2ch (h)
105	120	118.8	9.02E+04	1.13E+05
95	120	108.8	1.91E+05	2.38E+05
85	120	98.8	4.22E+05	5.26E+05
55	120	68.8	5.99E+06	7.47E+06
105	140	121.1	5.46E+04	6.80E+04
95	140	111.1	1.15E+05	1.43E+05
85	140	101.1	2.51E+05	3.12E+05
55	140	71.1	3.44E+06	4.29E+06

Tj of QD-LDs is lower than that of VCSELs due to low thermal resistance



The temperature difference (ΔT) between Ta and Tj for Si-photonic modules is less than 20℃

ΔT = 15℃ @140mA for actual measurement



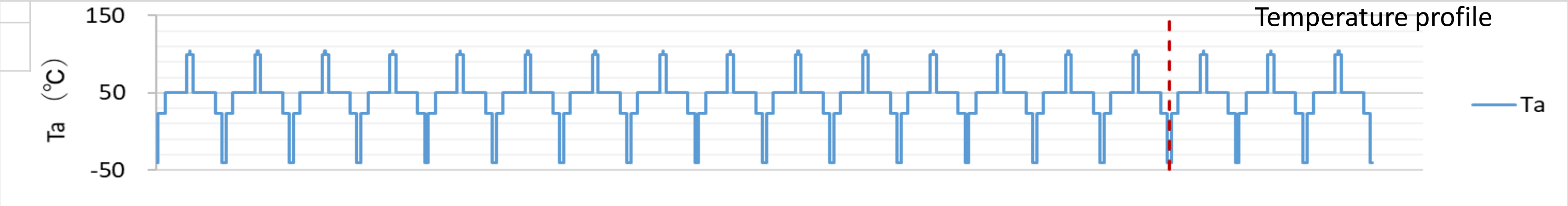
QD-LD lifetime estimate for automotive mission profile

	Wear-out	Random
Ea (eV)	0.969	0
Lognormal σ	0.664	-
ln(μ)_Base cond.	10.907	-
Random FIT_Base cond.	-	5
Base cond. Ta (°C)	105	
If (mA)	140	
Tj (°C)	121.1	

Operation Current (mA)	140	
Total operation time tm (h)	32000	
	Cumulative failure (ppm)	Mean FIT
2ch-LD @tm	161	5.0

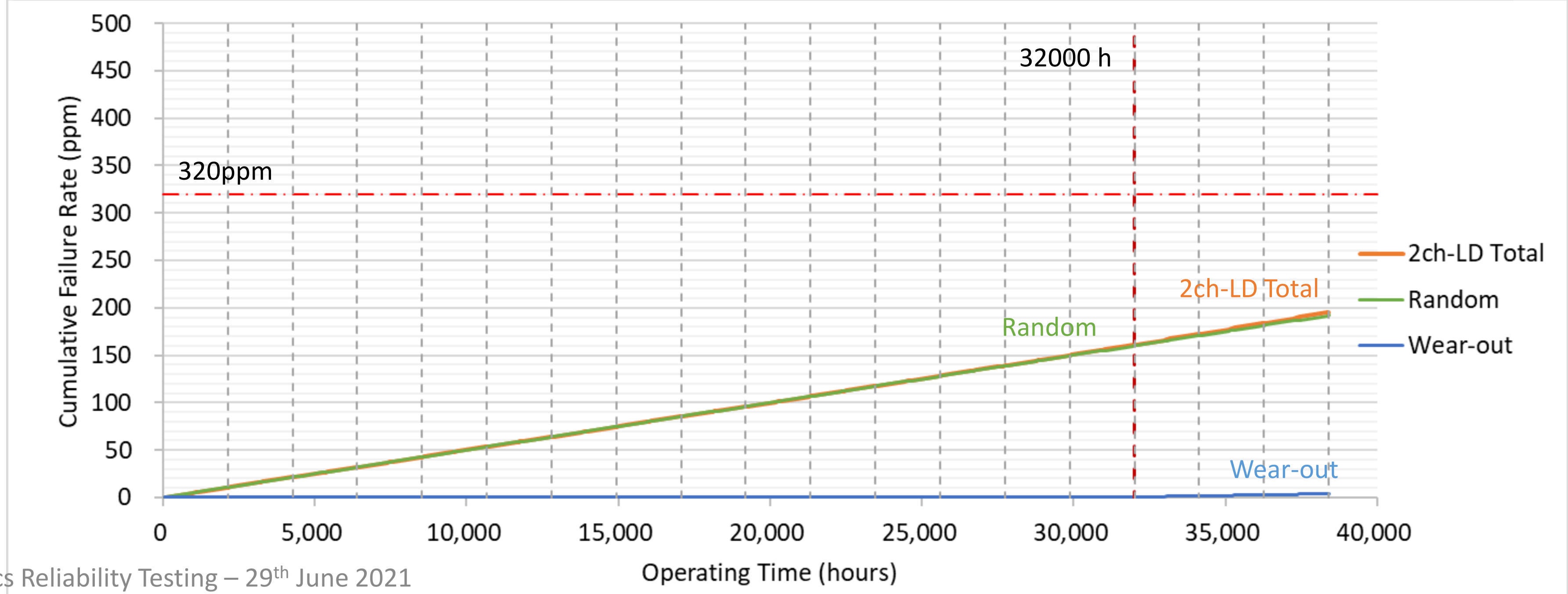
If=140mA 2ch-LD, Random=5Fit
Cumulative failure rate : 161 ppm
Mean FIT : 5.0 Fit

Wear-out failure rate is negligible small.
Failure rate is determined by random FIT.

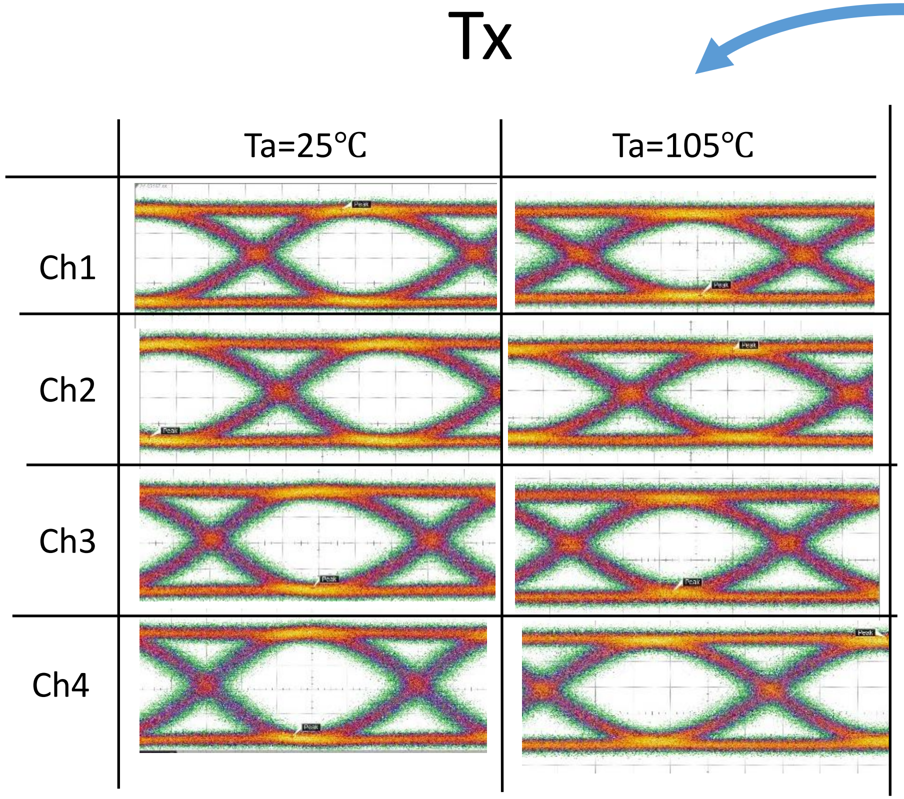


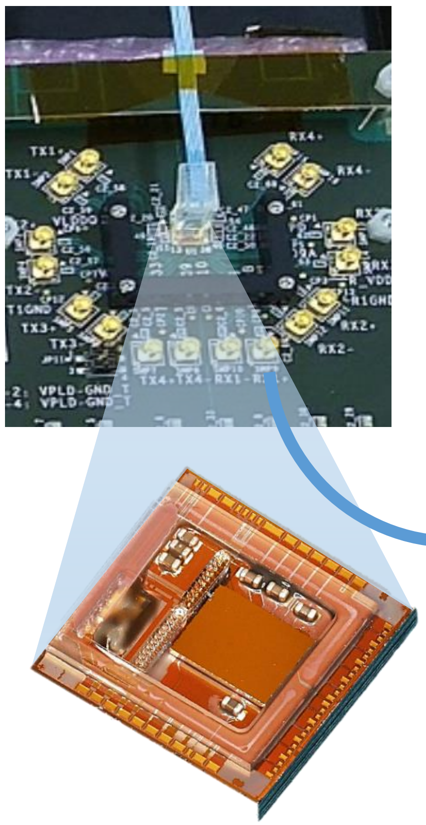
Cumulative failure rate vs Operating Time

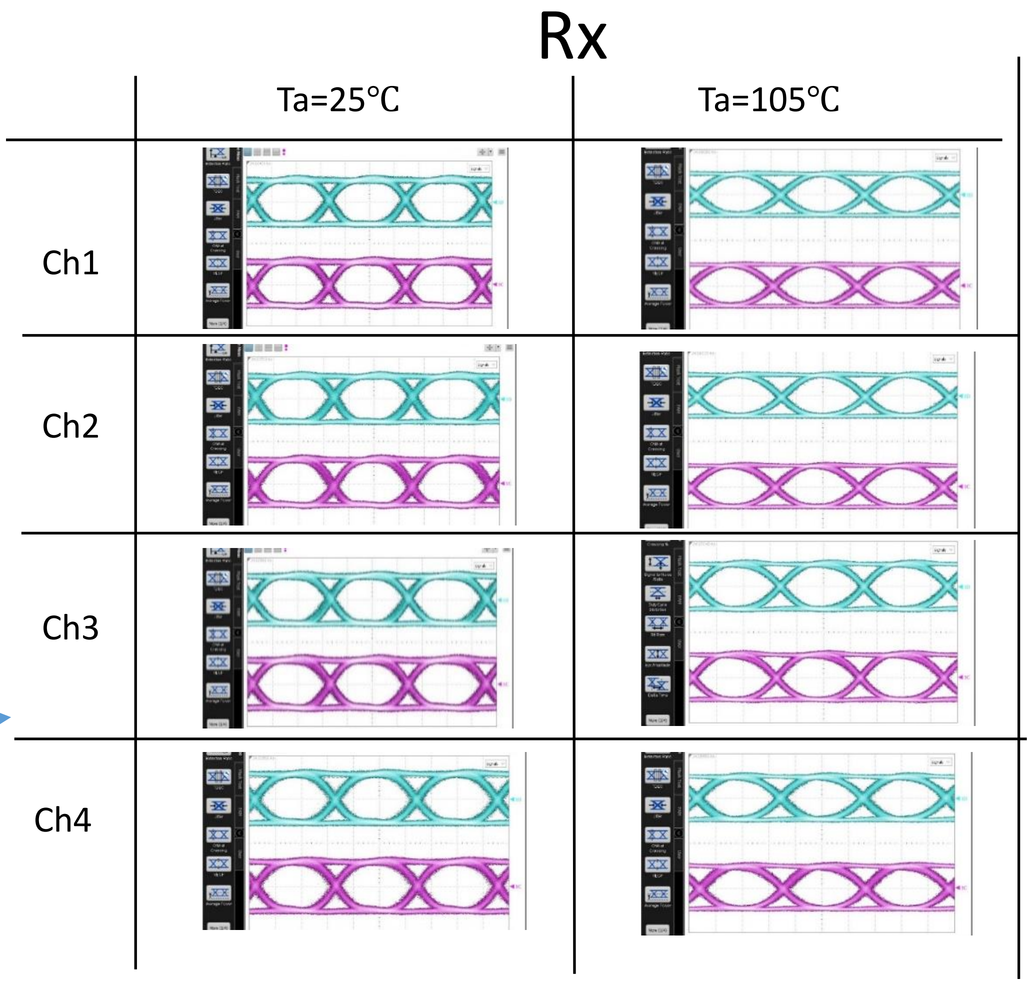
2ch-LD
EOL: ΔPo=-20%



Signal integrity analysis at 128 Gbps (32G x 4ch), 105 °C operation







32 Gbps PRBS^{31} - TX,RX All lanes active

32 Gbps PRBS^{31} - TX,RX All lanes active

Operational current region

Kurata, K. et al. "Short reach, high temperature operation and high reliability silicon photonic micro-transceivers for embedded and co-packaged system integration," Proc. SPIE 11692, Optical Interconnects XXI, 1169204 (16 March 2021); https://doi.org/10.1117/12.2576670

Advantage of QD-LD: Resistance to DLD induced sudden failure

QD-LD

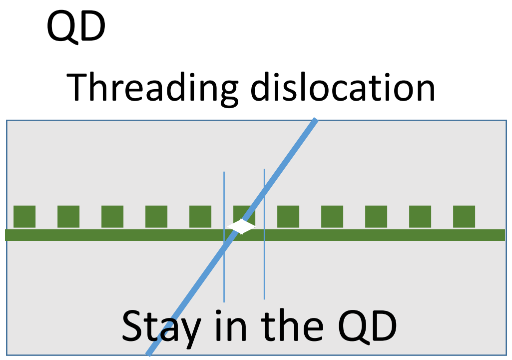
Active layer: InAs/GaAs quantum dot (QD) isolated in a plane

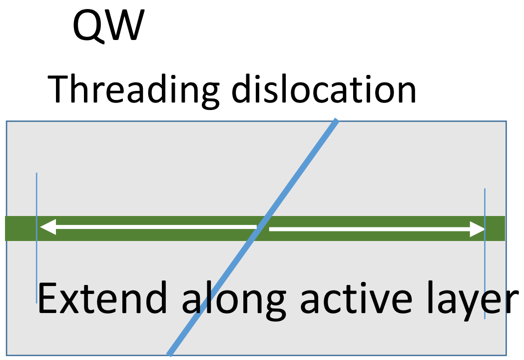
Dislocation motion is reduced by localized carriers in QDs, which suppresses DLD induced sudden failure.[1)]

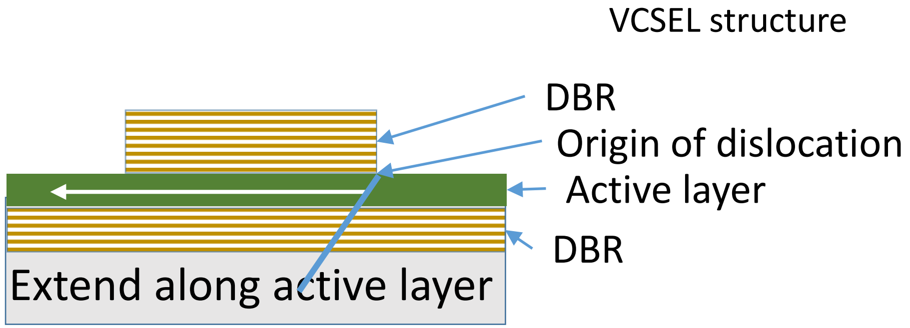
VCSEL

Active layer: (In)GaAs quantum well (QW) spreading in a plane

Dislocation motion is enhanced by diffused carriers in QW layers, which leads to sudden failure due to DLD formation.2)







1) T. Kageyama, 27 Nov.,2019 Optoelectronics ＆Technology Development Association Workshop
2) Materials and Reliability Handbook for Semiconductor Optical and Electron Devices(2013) pp150-205

The main advantage of QD-LDs are resistance to sudden failure and low thermal resistance.

Quantum Dot laser reliability

Fabry Perot Quantum Dot laser

- Strong and increasing industry support due to superior performance, stability at high temperatures
- **Intel paper:** J. C. Norman et al., "A Review of High-Performance Quantum Dot Lasers on Silicon," in IEEE Journal of Quantum Electronics, vol. 55, no. 2, pp. 1-11, April 2019, Art no. 2000511, doi: 10.1109/JQE.2019.2901508

FIT rate of QD-LDs is estimated to be 1.7 FIT based on total shipment of 3.2Mpcs and total 1.4×10^{11} component hours.

Questions about 850 nm and 980 nm VCSEL suitability

850 nm VCSELs – strong questions about reliability for target environment

Pros	Cons
850 nm has been deployed in the field as a datacom transceiver for over 20 years.	Based on different contributions, 850 nm VCSEL reliability in the target environment seems strongly questionable.
It has benefited from two decades of design and manufacturing optimisation. Shows excellent reliability in data centre environments	Results from calculations vary between failure and pass depending on small changes in choice of activation energy E_a figure and delta between junction temperature T_j and T_a. Environmental testing is non-conclusive.

940nm / 980 nm VCSELs - more reliable, but no field deployment history for optical datacom

Pros	Cons
980 nm shows better reliability results than 850 nm in target environment	It has only been used for sensing. It has no field deployment history for datacom. No standards advocate 980 nm, no transceivers use 980nm VCSELs, its performance has only been shown in labs

Please avoid false equivalency between 850nm and 940nm or 980 nm VCSELs.
There is no composite "850nm/980nm" VCSEL, which combines the long field deployment history of 850 nm and the higher reliability of 980 nm. <u>850 nm and 980 nm are not the same.</u>

Exclusion of silicon photonics difficult to justify

Question

In 2026, when this standard will most likely be sought in earnest, silicon photonics will be the dominant optical transceiver by revenue* and is inherently more reliable than directly modulated VCSEL solutions. **How will we justify having completely excluded it from consideration and choosing only VCSEL based PMDs?**

Proposal

No need to choose all 28 PMDs, but for the first batch of PMDs we should at least choose **the most useful PMDs in terms of reliability or cost** to give automakers the choice. **Propose that the first batch of PMDs include VCSELs for at least lower data rates but should also include silicon photonics at least for the higher data rate 25G over OM3 and POF to give automakers the choice between the best of both worlds.**

* **Recommended source:** Online Lightwave article: https://www.lightwaveonline.com/business/market-research/article/14204210/lightcounting-silicon-photonics-overhyped-nah

Contributions and technical references

I. Ogura (PETRA) and K. Kurata (AIO Core) have published many scientific papers and made numerous contributions to IEEE 802.3cz on their devices alone (shown below)

Generally there is a vast body of technical publications on 1310 nm silicon photonics transceivers

Contributions to 802.3cz

- **March 2021:** Response to Proposal Assumptions
- **March 2021**: A proposal of Si-photonics for automobile
- **January 2021**: Thoughts on PMD baseline proposal for automobile based on Si-Photonics
- **January 2020**: A study for highly-reliable optical transceiver based on Si Photonics technology
- **November 2019**: Introduction of SI Photonics transceiver technology with High temperature operation capability and MMF transmission

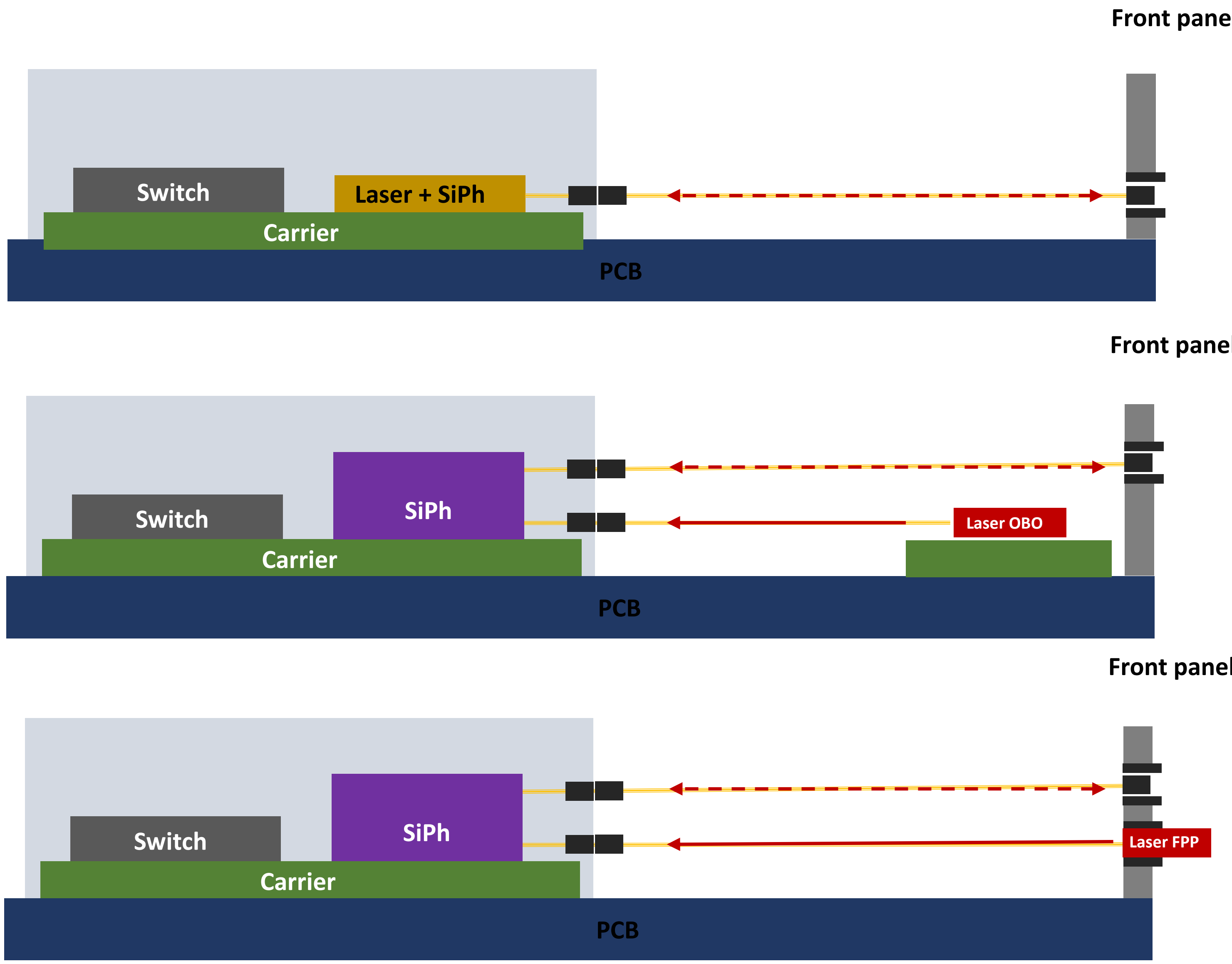
Technical publications

1. Kurata, K. et al., “"Short reach, high temperature operation and high reliability silicon photonic micro-transceivers for embedded and co-packaged system integration", Proc. SPIE 11692, Optical Interconnects XXI, 1169204 (16 March 2021); https://doi.org/10.1117/12.2576670
2. Kurata, K. et al., “Short reach, low-cost silicon photonic micro-transceivers for embedded and co-packaged system integration,” Proc. SPIE 11286, Optical Interconnects XX, 112860R (28 February 2020); https://doi.org/10.1117/12.2546626
3. Pitwon, R., O’Faolain, L., Kurata, K., Lee, B., Ninomiya, T., "Hyperscale Integrated Optical and Photonic Interconnect Platform," 2020 IEEE Photonics Conference (IPC), Vancouver, BC, Canada, 2020, pp. 1-2, doi: 10.1109/IPC47351.2020.9252246.
4. Nakamura, T. et al., “Fingertip-Size Optical Module, “Optical I/O Core”, and Its Application in FPGA” IEICE TRANSACTIONS on Electronics, Vol.E102-C, No.4, pp.333-339
5. Mogami, T. et al., "1.2 Tbps/cm2 Enabling Silicon Photonics IC Technology Based on 40-nm Generation Platform," J. Lightwave Technol. 36, 4701-4712 (2018)
6. K. Kurata, I. Ogura, K. Yashiki and Y. Suzuki, "Chip-scale si-photonics optical transceiver for a photonics-electronics convergence system (invited paper)," 2016 Tenth IEEE/ACM International Symposium on Networks-on-Chip (NOCS), Nara, Japan, 2016, pp. 1-6, doi: 10.1109/NOCS.2016.7579338.

THANK YOU

Integrated vs remote lasers

Integrated lasers
Lasers integrated into SiPh chiplet
- Serviceability
+ Lowest total power
+ Better testability
+ Lowest Cost



Remote lasers
Separate on-board modules or front pluggable modules
- Highest laser loss to PIC (> 4dB)
- PM fibre required between lasers and PIC
+ Better serviceability
+ Lowest thermal density

Co-packaged optics is driving silicon photonics evolution