# VCSELs Performance measurements and reliability analysis

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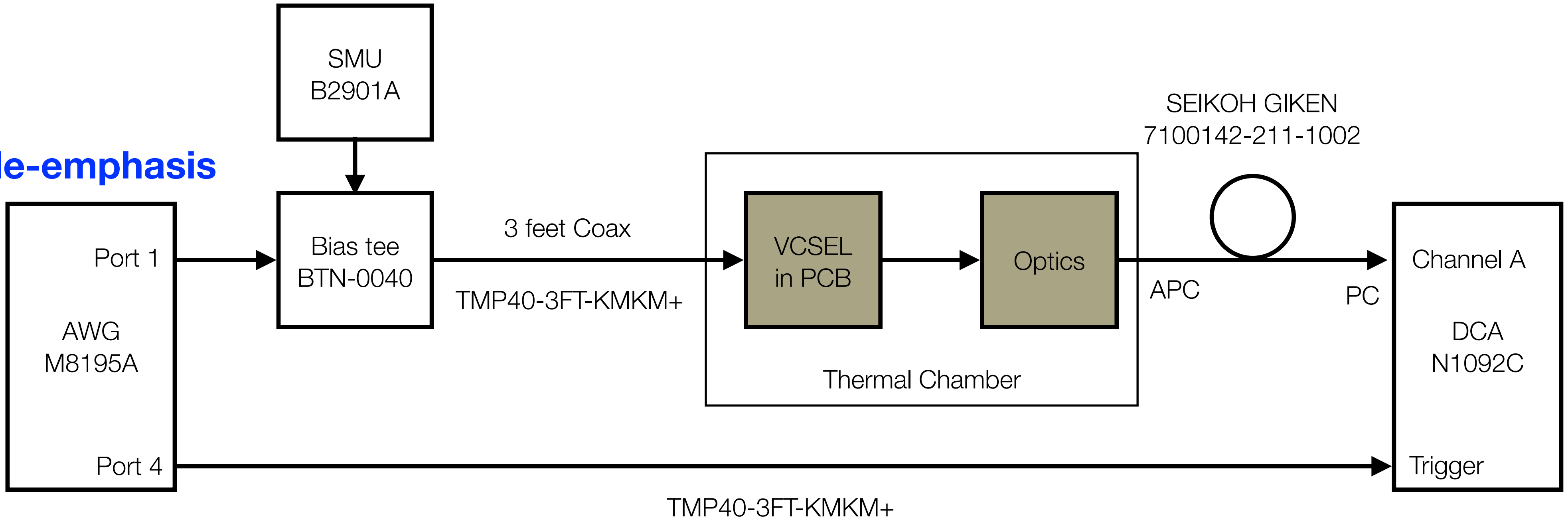
**IEEE 802.3dh Task Force - 5th Oct 2022 Ad-hoc Meeting**

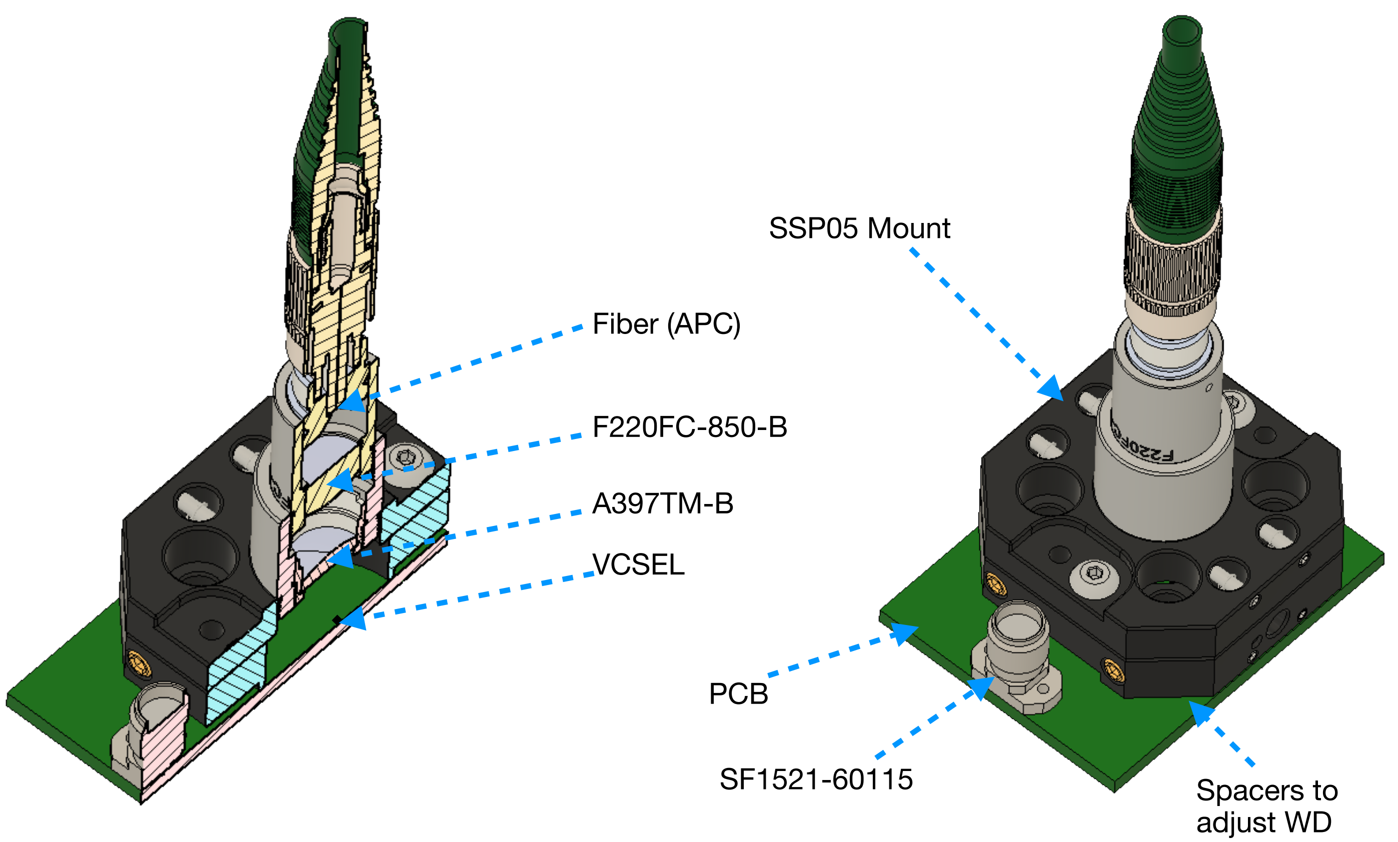
# Performance measurements

- Test results of 850nm 25Gbps VCSELs supplied by different vendors, as already reported at perezaranda_OMEGA_01b_0720_VCSEL_test_methods
- Results for same devices were already presented at https://www.ieee802.org/3/cz/public/jul_2020/index.html
- Test results for 980nm VCSEL are also provided for comparison

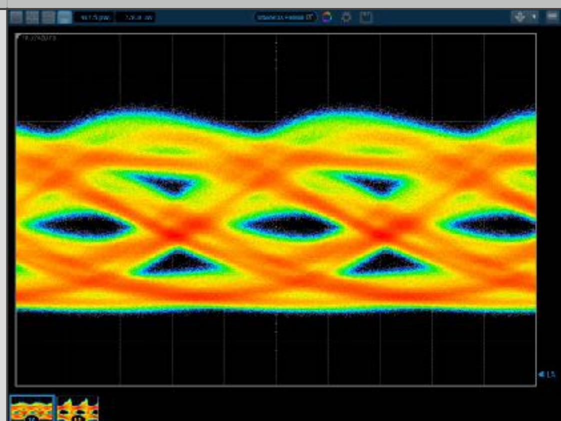
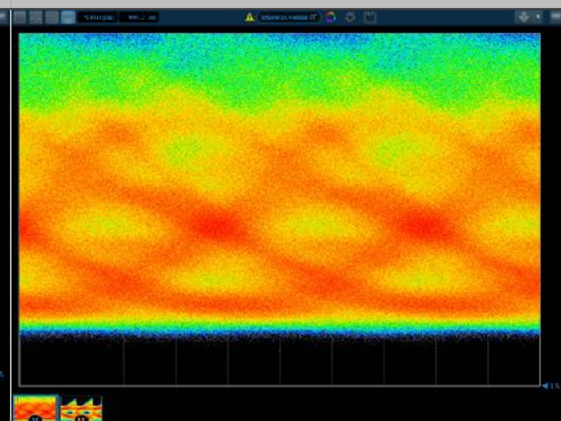
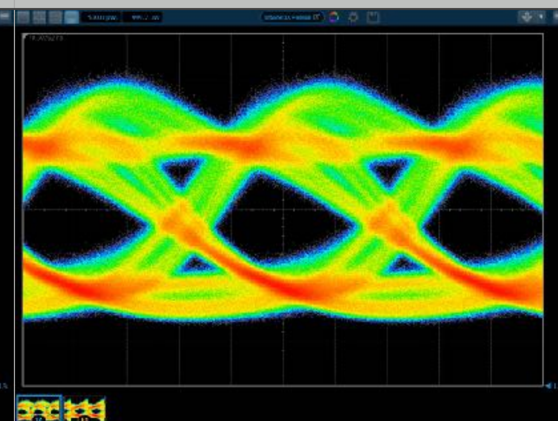
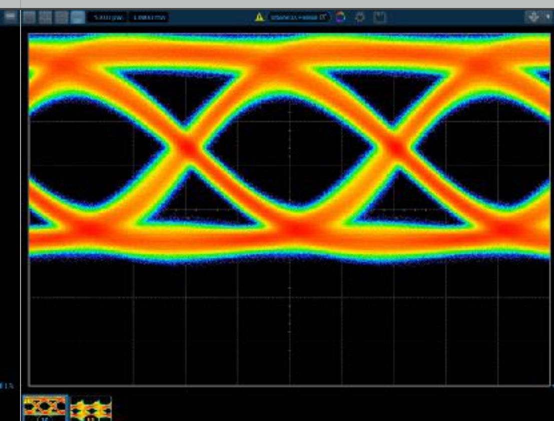
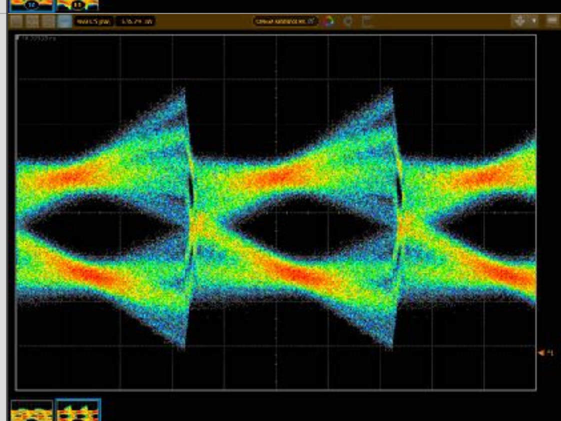
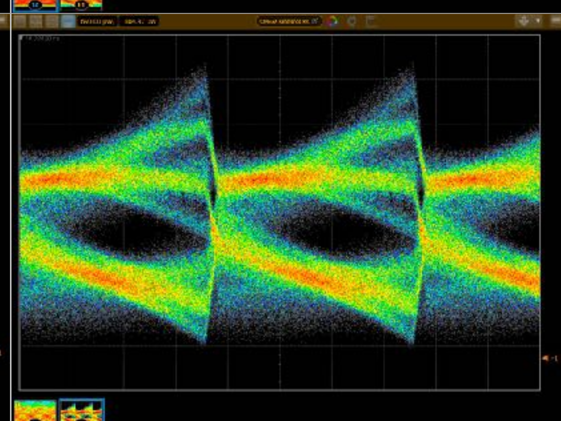
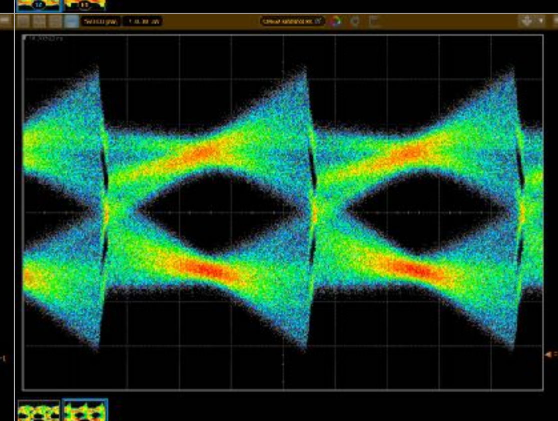
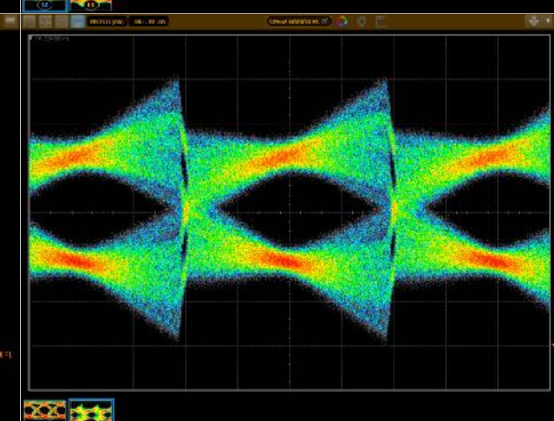
# Test setup

**NO pre/de-emphasis**

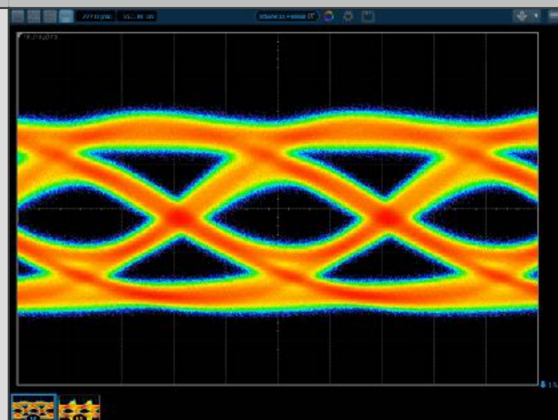
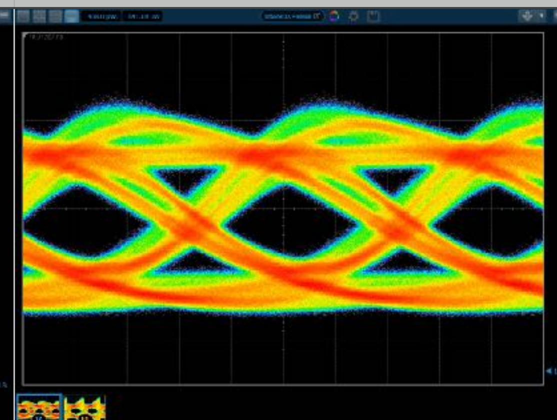
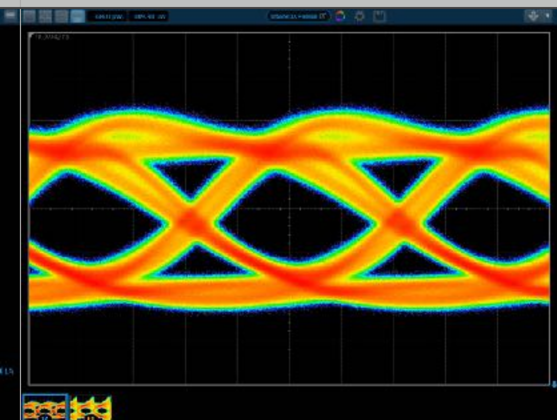
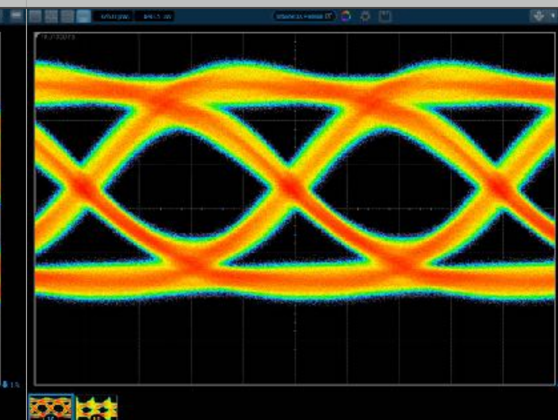
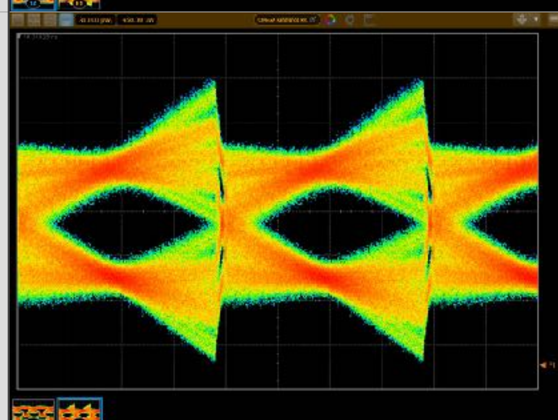
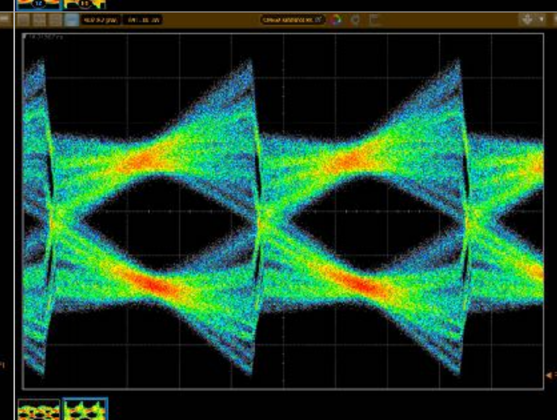
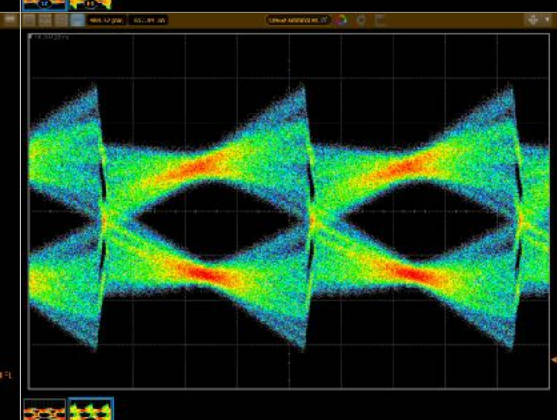
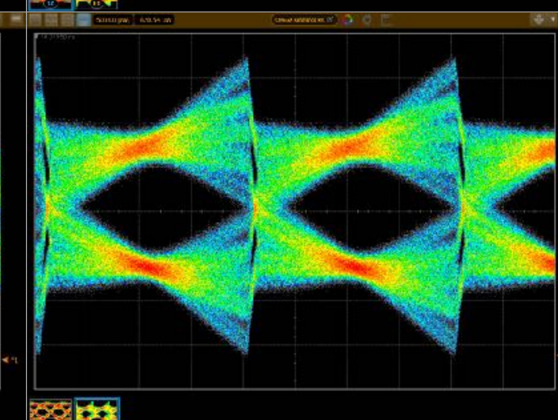


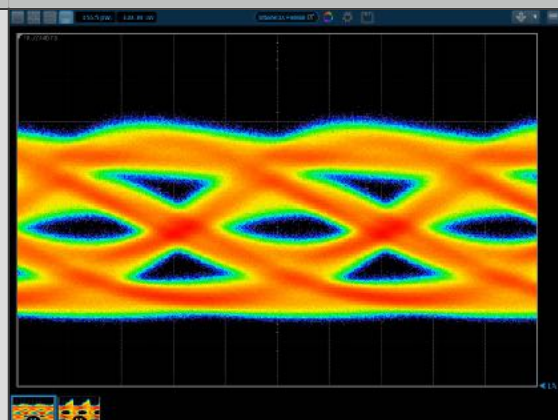
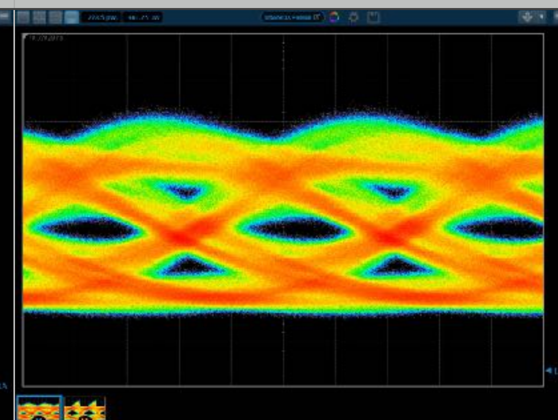
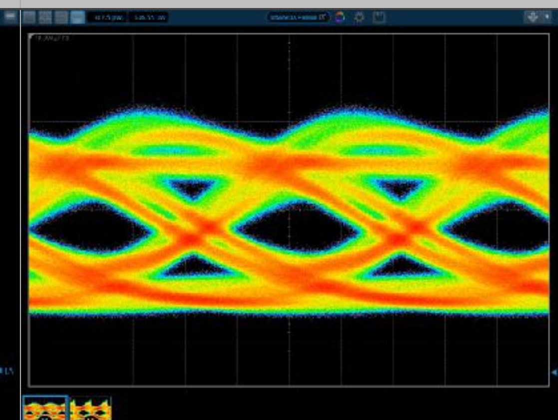
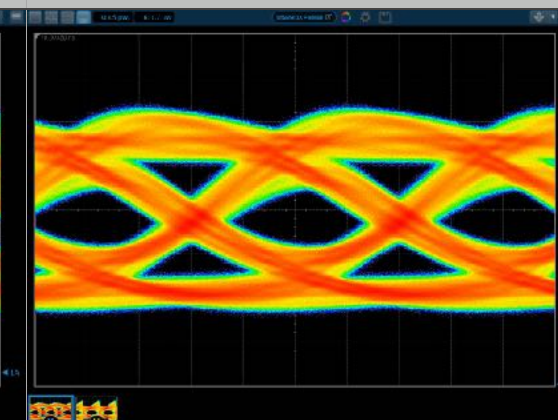
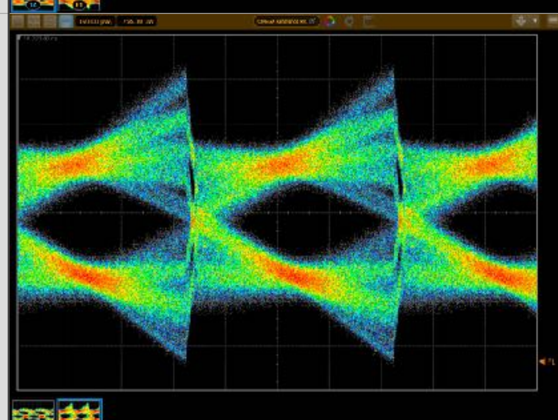
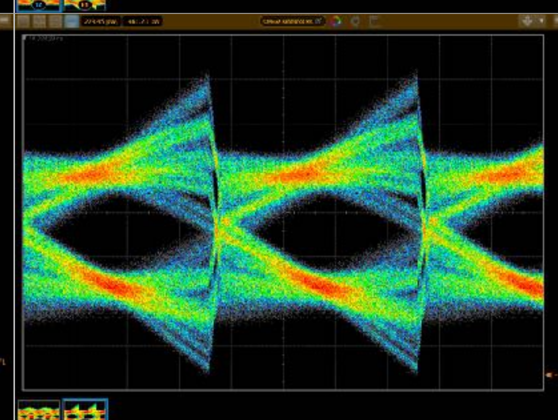
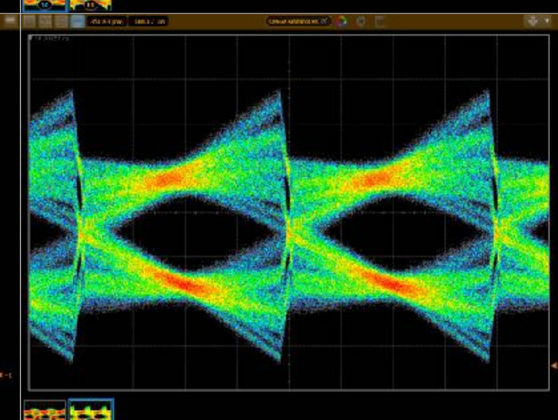
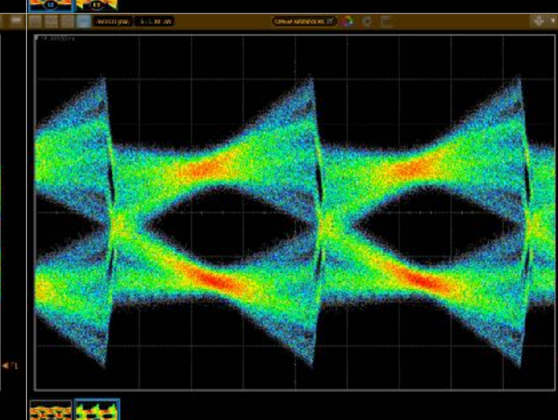

# Performance at $T_{BS}$ = -40°C, 25 Gbps NRZ

| | VCSEL 850 nm | | | VCSEL 980nm |
|---|---|---|---|---|
| | Device 1 | Device 2 | Device 3 | Device 4 |
| Eye diagram w/ 0.75x BT4 |  |  |  |  |
| 802.3.cz Reference RX |  |  |  |  |
| $I_{BIAS}$ (mA) recomended | 7 | 5 | 7 | 7 |
| ER (dB) | 3.98 | 3.99 | 4.01 | 3.77 |
| OMA (dBm) | 0.98 | 2.44 | 2.26 | 3.19 |
| 802.3.cz TDFOM (dB) | 1.06 | 7.89 | 0.33 | 1.17 |
| $RIN_{OMA}$ (dB/Hz) | -130.1 | -127.3 | -130.9 | -144.6 |

# Performance at $T_{BS}$ = 85°C, 25 Gbps NRZ

| | VCSEL 850 nm | | | VCSEL 980nm |
|---|---|---|---|---|
| | Device 1 | Device 2 | Device 3 | Device 4 |
| Eye diagram w/ 0.75x BT4 |  |  |  |  |
| 802.3.cz Reference RX |  |  |  |  |
| $I_{BIAS}$ (mA) recomended | 7 | 5 | 7 | 7 |
| ER (dB) | 4.00 | 4.36 | 4.04 | 3.99 |
| OMA (dBm) | -0.64 | 1.31 | 1.29 | 1.64 |
| 802.3.cz TDFOM (dB) | 1.24 | 0.59 | 0.60 | 0.88 |
| $RIN_{OMA}$ (dB/Hz) | -130.7 | -131.7 | -130.9 | -140.4 |

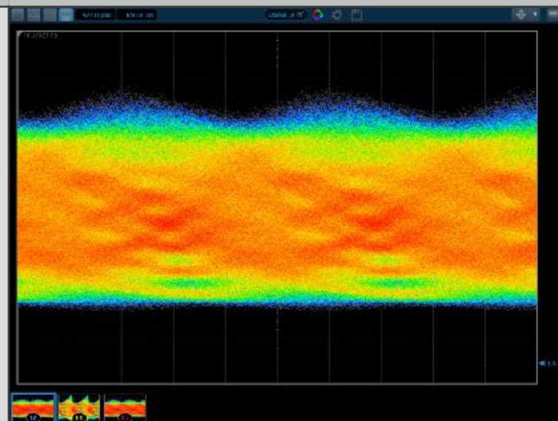
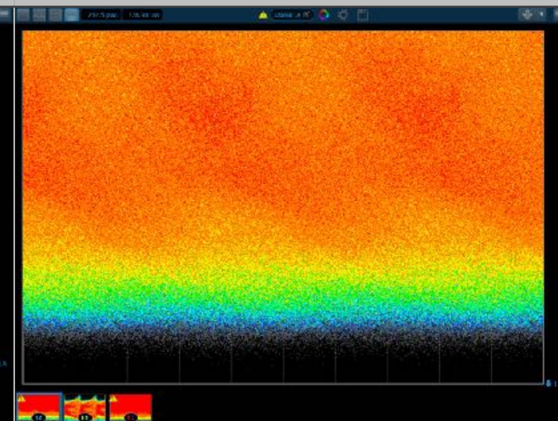
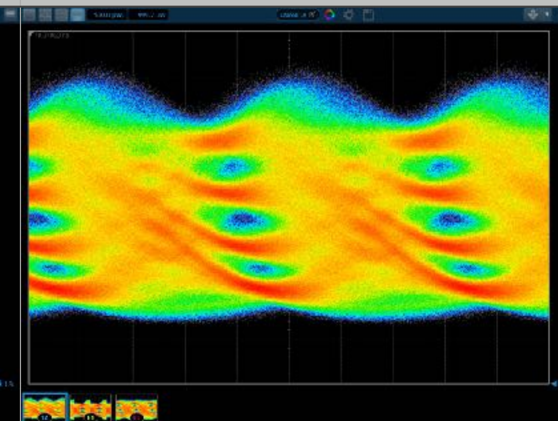
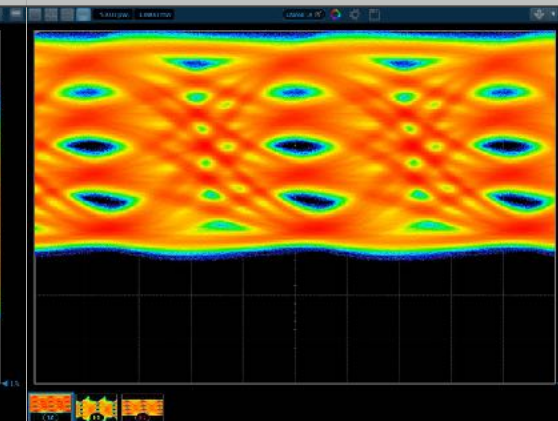
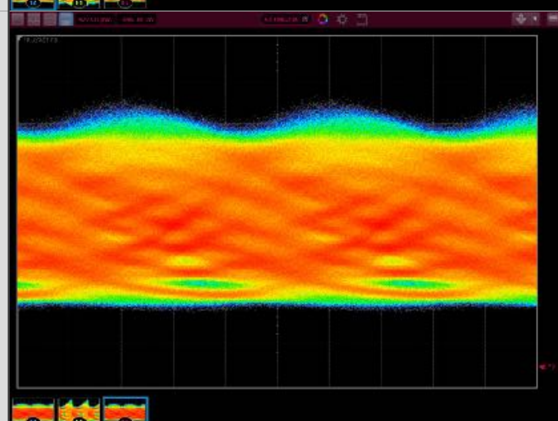
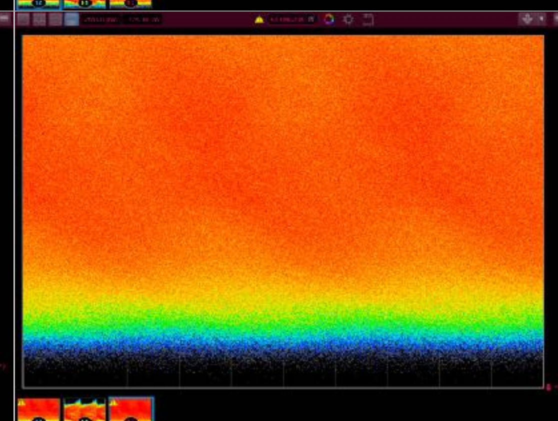
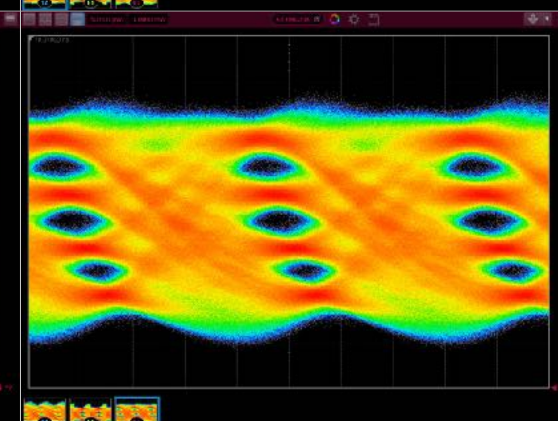
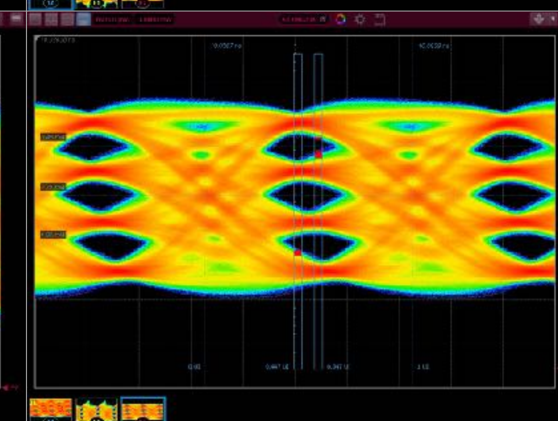
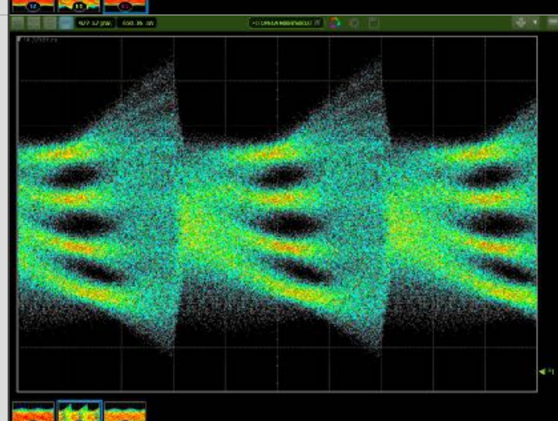
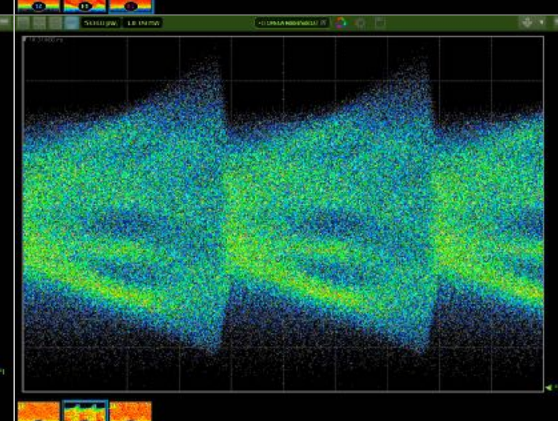
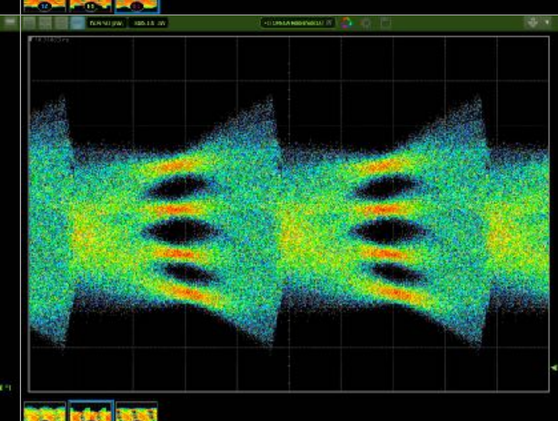
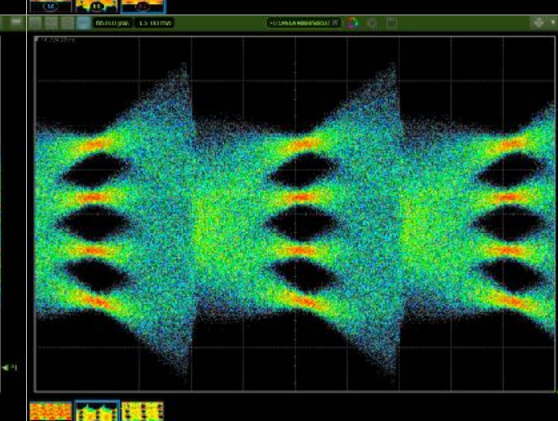
# Performance at $T_{BS}$ = 125°C, 25 Gbps NRZ

| | VCSEL 850 nm | | | VCSEL 980nm |
|---|---|---|---|---|
| | Device 1 | Device 2 | Device 3 | Device 4 |
| Eye diagram w/ 0.75x BT4 |  |  |  |  |
| 802.3.cz Reference RX |  |  |  |  |
| $I_{BIAS}$ (mA) recomended | 7 | 5 | 7 | 7 |
| ER (dB) | 4.06 | 4.02 | 4.09 | 4.09 |
| OMA (dBm) | -2.73 | -1.05 | -0.19 | 0.30 |
| 802.3.cz TDFOM (dB) | 1.25 | 0.74 | 0.56 | 0.91 |
| $RIN_{OMA}$ (dB/Hz) | -129.3 | -128.5 | -132.1 | -138.0 |

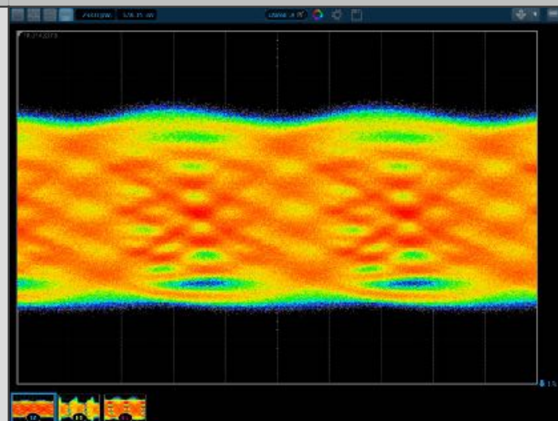
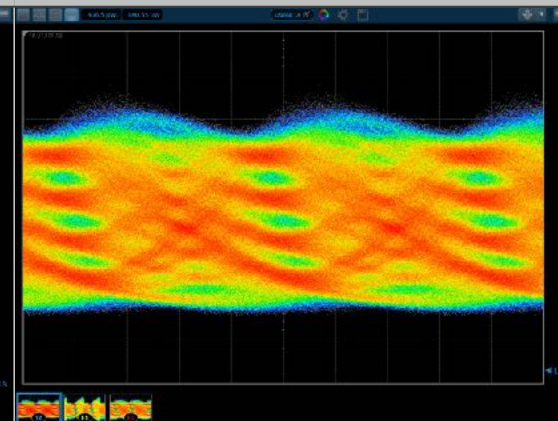
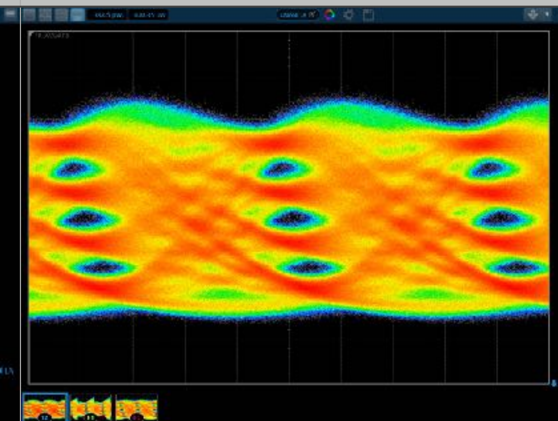
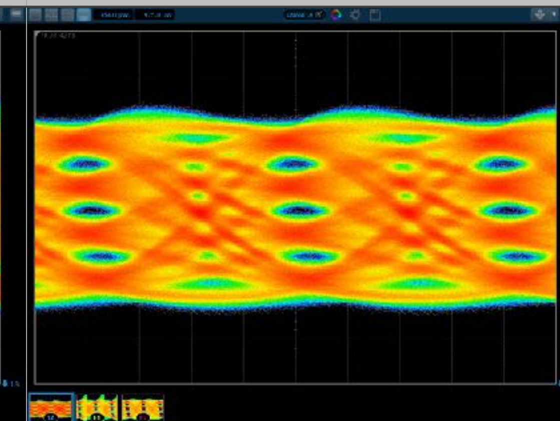
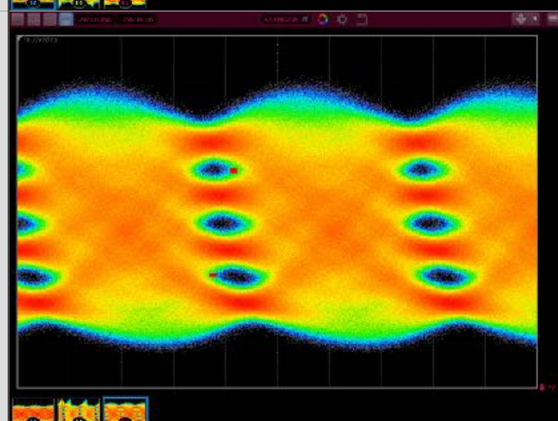
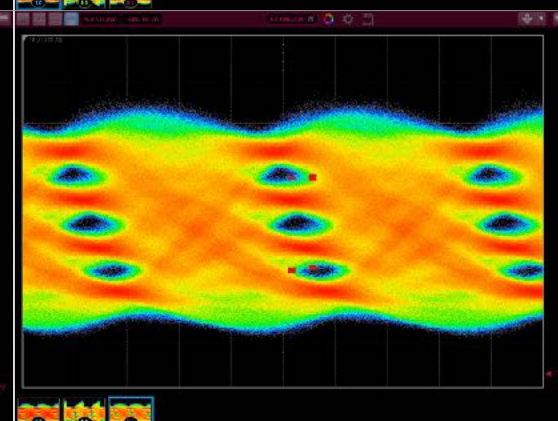
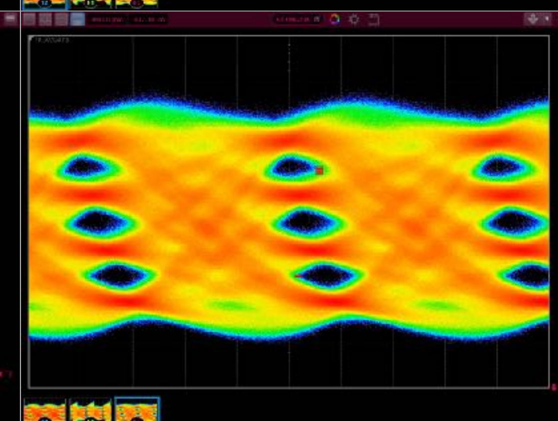
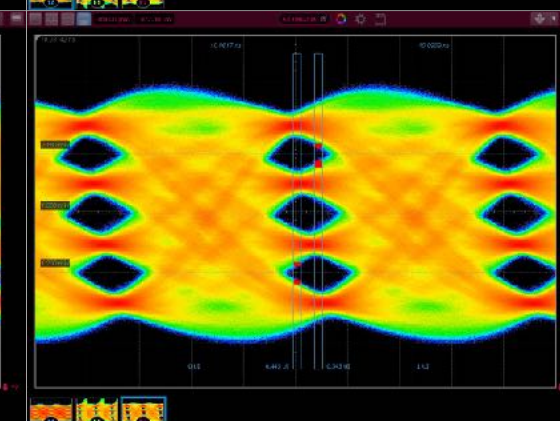
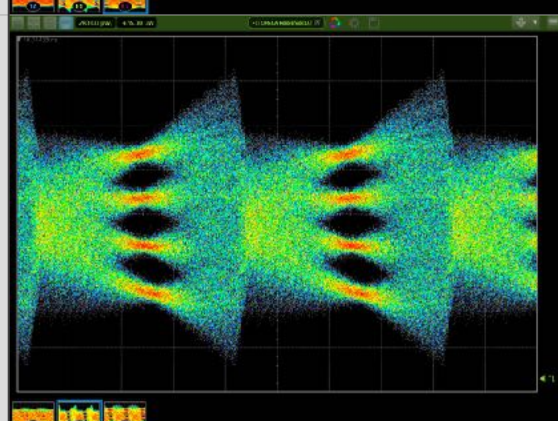
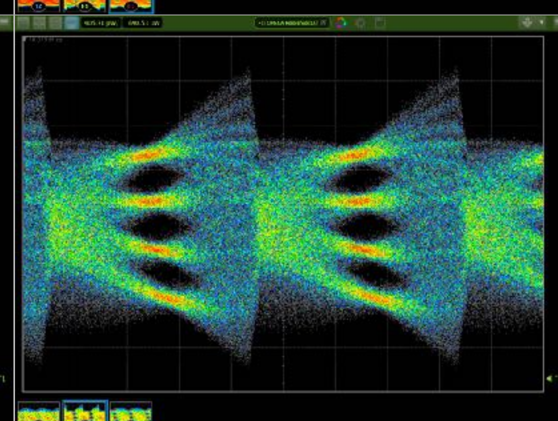
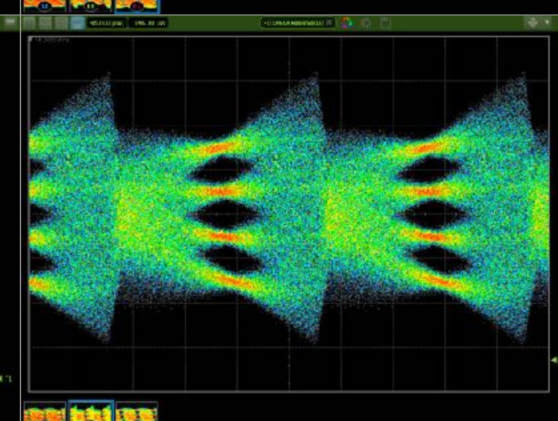
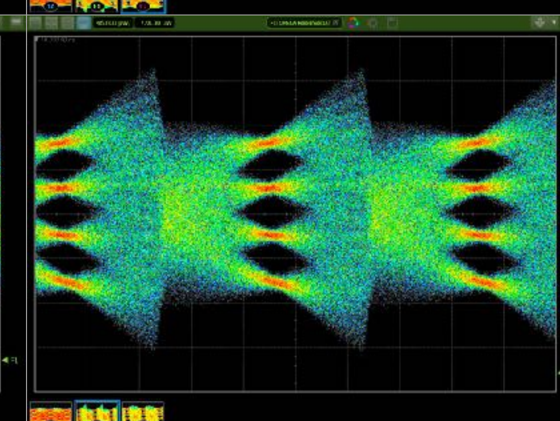
# Performance of 25 Gbps NRZ, summary

- RIN OK
- TDFOM is OK in general in high temperature for 850nm
- One of the tested VCSELs is not able to operate at cold
- OMA is degraded with high temperature; only one 850nm VCSEL passed OMA requirement (TDFOM dependent)
- It is clear the superiority of 980nm in the full temperature range
- TX performance evaluation has been carried out based on 802.3cz test methods, which guarantee interoperability to meet automotive link budget requirements
- **Despite the fact that a 850nm VCSEL can be produced to meet 25 Gb/s 802.3cz TX characteristics, the wear-out reliability is the limitation for the considered mission profile (see next slides)**
- Even though 50 Gb/s is not a 802.3dh objective, the following slides show some results for PAM4 50 Gb/s, which reinforce why 980nm was selected in 802.3cz

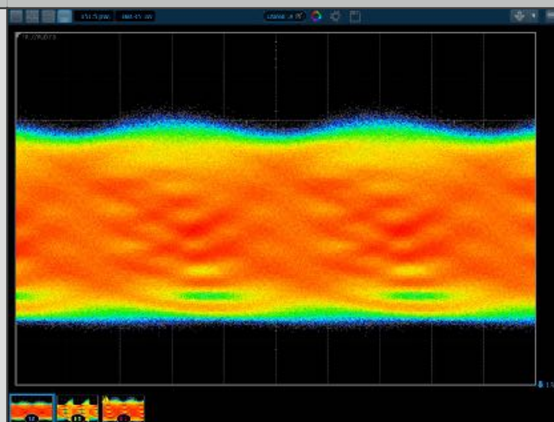
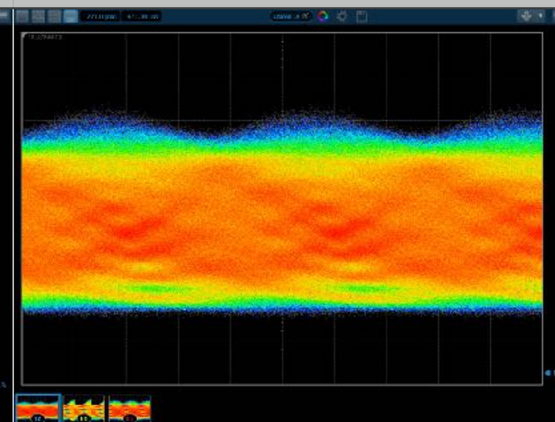
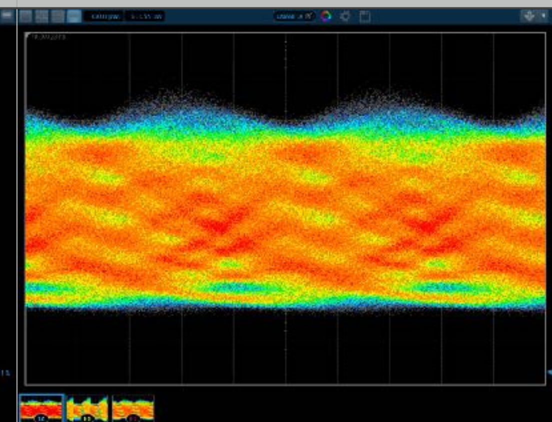
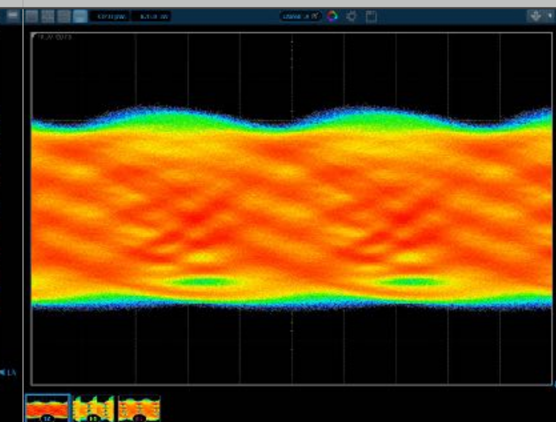
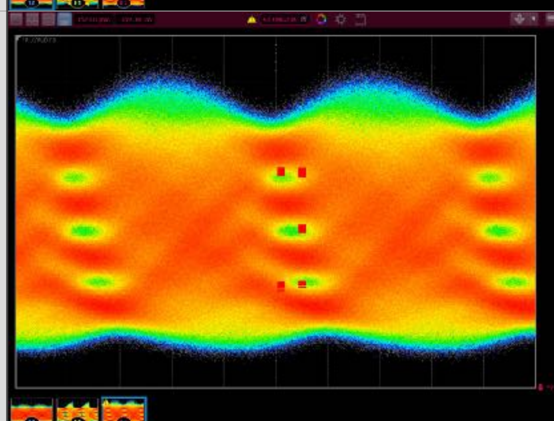
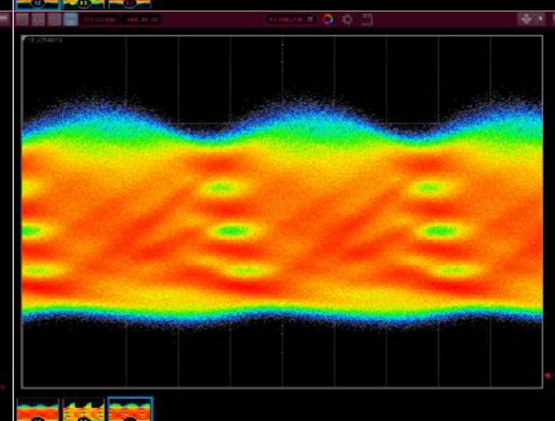
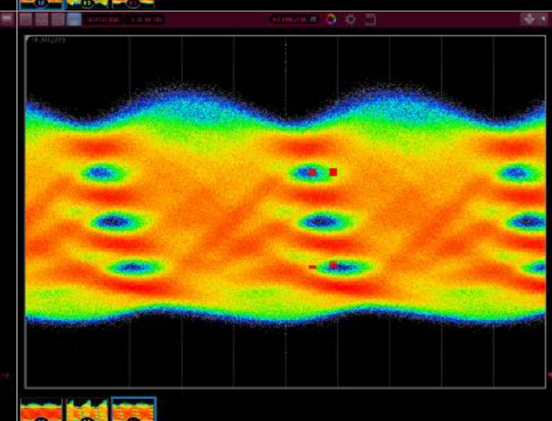
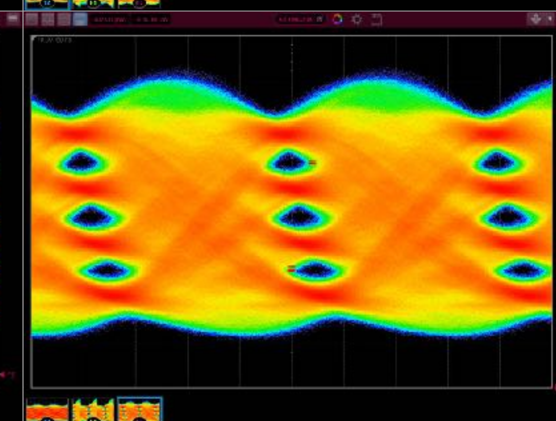
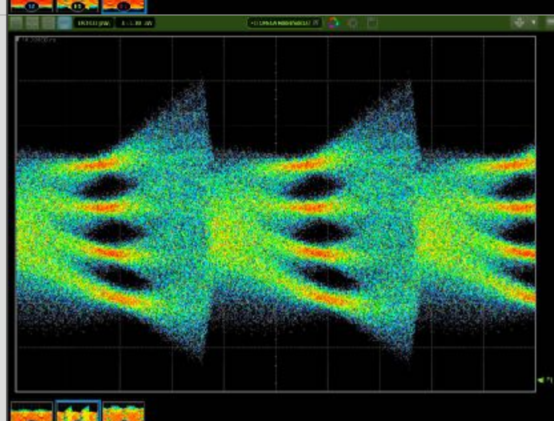
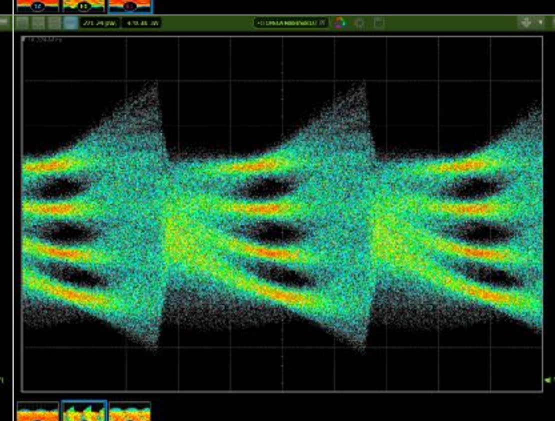
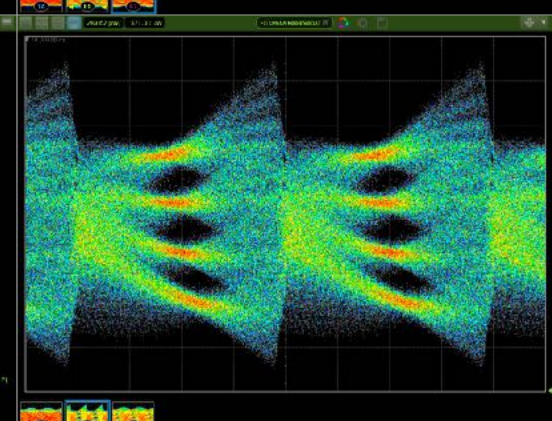
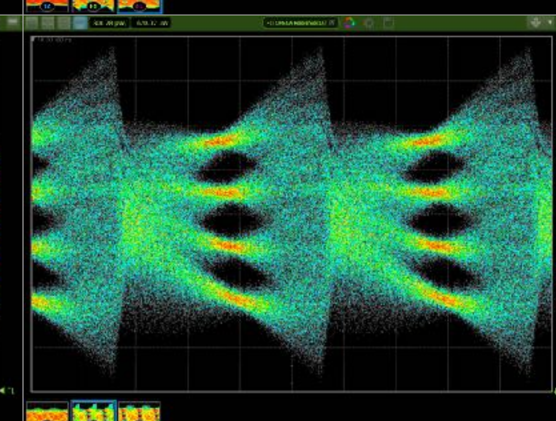
# Performance at $T_{BS}$ = -40ºC, 50 Gb/s PAM4

| | VCSEL 850 nm | | | VCSEL 980nm |
|---|---|---|---|---|
| | Device 1 | Device 2 | Device 3 | Device 4 |
| Eye diagram w/ 0.75x BT4 |  |  |  |  |
| TDECQ Eq |  |  |  |  |
| 802.3.cz Reference RX |  |  |  |  |
| $I_{BIAS}$ (mA) recomended | 7 | 5 | 7 | 7 |
| ER (dB) | 4.12 | 5.19 | 4.06 | 3.91 |
| 802.3.cz TDFOM (dB) | 12.57 | 29.92 | 2.87 | 1.84 |

# Performance at $T_{BS}$ = 85ºC, 50 Gb/s PAM4

| | VCSEL 850 nm | | | VCSEL 980nm |
|---|---|---|---|---|
| | Device 1 | Device 2 | Device 3 | Device 4 |
| Eye diagram w/ 0.75x BT4 |  |  |  |  |
| TDECQ Eq |  |  |  |  |
| 802.3.cz Reference RX |  |  |  |  |
| $I_{BIAS}$ (mA) recomended | 7 | 5 | 7 | 7 |
| ER (dB) | 4.05 | 4.02 | 4.01 | 3.97 |
| 802.3.cz TDFOM (dB) | 2.34 | 2.40 | 1.18 | 1.70 |

# Performance at $T_{BS}$ = 125°C, 50 Gb/s PAM4

| | VCSEL 850 nm | | | VCSEL 980nm |
|---|---|---|---|---|
| | Device 1 | Device 2 | Device 3 | Device 4 |
| Eye diagram w/ 0.75x BT4 |  |  |  |  |
| TDECQ Eq |  |  |  |  |
| 802.3.cz Reference RX |  |  |  |  |
| $I_{BIAS}$ (mA) recomended | 7 | 5 | 7 | 7 |
| ER (dB) | 3.92 | 3.75 | 4.03 | 4.04 |
| 802.3.cz TDFOM (dB) | 5.32 | 10.34 | 4.87 | 2.85 |

# Reliability model

# Wear-out reliability model — unreliability function

$$TTF_{x\%} = C \cdot J^{-n} \cdot \exp\left(\frac{E_a \cdot e}{k_B \cdot T_J}\right) = F^{-1}\left(\frac{x}{100}\right); \quad F(t) = \Phi\left(\frac{\ln(t) - \mu'}{\sigma'}\right)$$

$$F(t) = \int_0^t f(\tau)d\tau$$

$$f(t) = \frac{dF}{dt}(t), \; f(t) \geq 0 \text{ for } \forall t \geq 0, \; \int_0^\infty f(\tau)d\tau = 1$$

$$f(t') = \frac{1}{\sigma'\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{t'-\mu'}{\sigma'}\right)^2\right)$$

$$MTTF = \int_0^\infty \tau f(\tau)d\tau$$

$$TTF_{1\%} = F^{-1}(0.01)$$

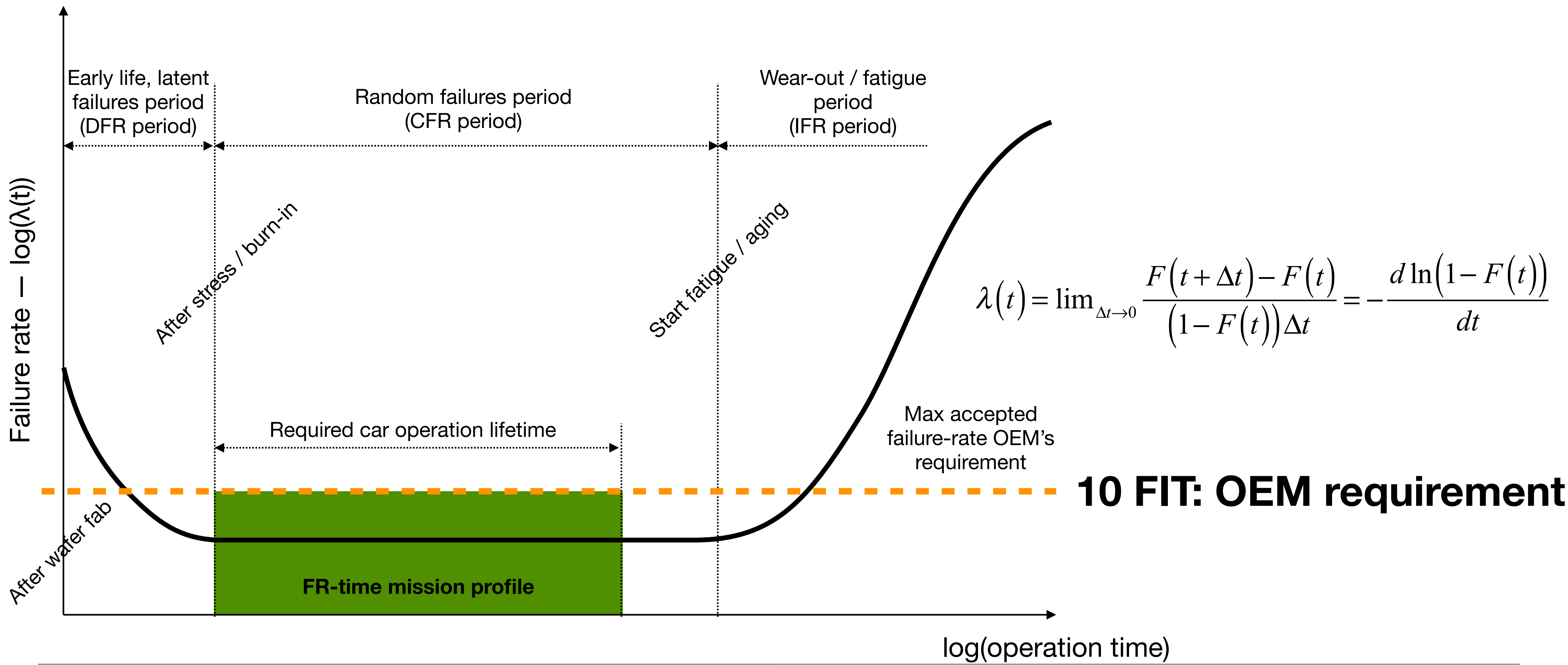
$$TTF_{50\%} = F^{-1}(0.5) = \exp(\mu')$$

$$TTF_{x\%} = \exp\left(\mu' + \sigma' \cdot \Phi^{-1}\left(\frac{x}{100}\right)\right)$$

- For a given *t*, *F(t)* is the probability that failure occurs before *t*
- *F(t)* is the cumulative distribution function (CDF) of the failure probability
  - Φ is the standard normal distribution (i.e. N(0,1))
  - *t* is the time to failure
  - *t'* is the natural logarithm of the time to failure
  - *μ'* mean of the natural logarithms of the time to failure
  - *σ'* standard deviation of the natural logarithms of the time to failure
- Arrhenius's equation
  - $E_a$ is the activation energy of failure mechanism (eV)
  - *e* is the electron charge (SI units)
  - $k_B$ is the Boltzmann's constant (SI units)
  - $T_J$ is absolute temperature (Kelvin)
  - *J* is the current density (e.g. in $kA/cm^2$)
  - *n* is the current exponent
  - *C* is a constant
  - $TTF_{x\%}$ is the time to x% failures (e.g. in hours)

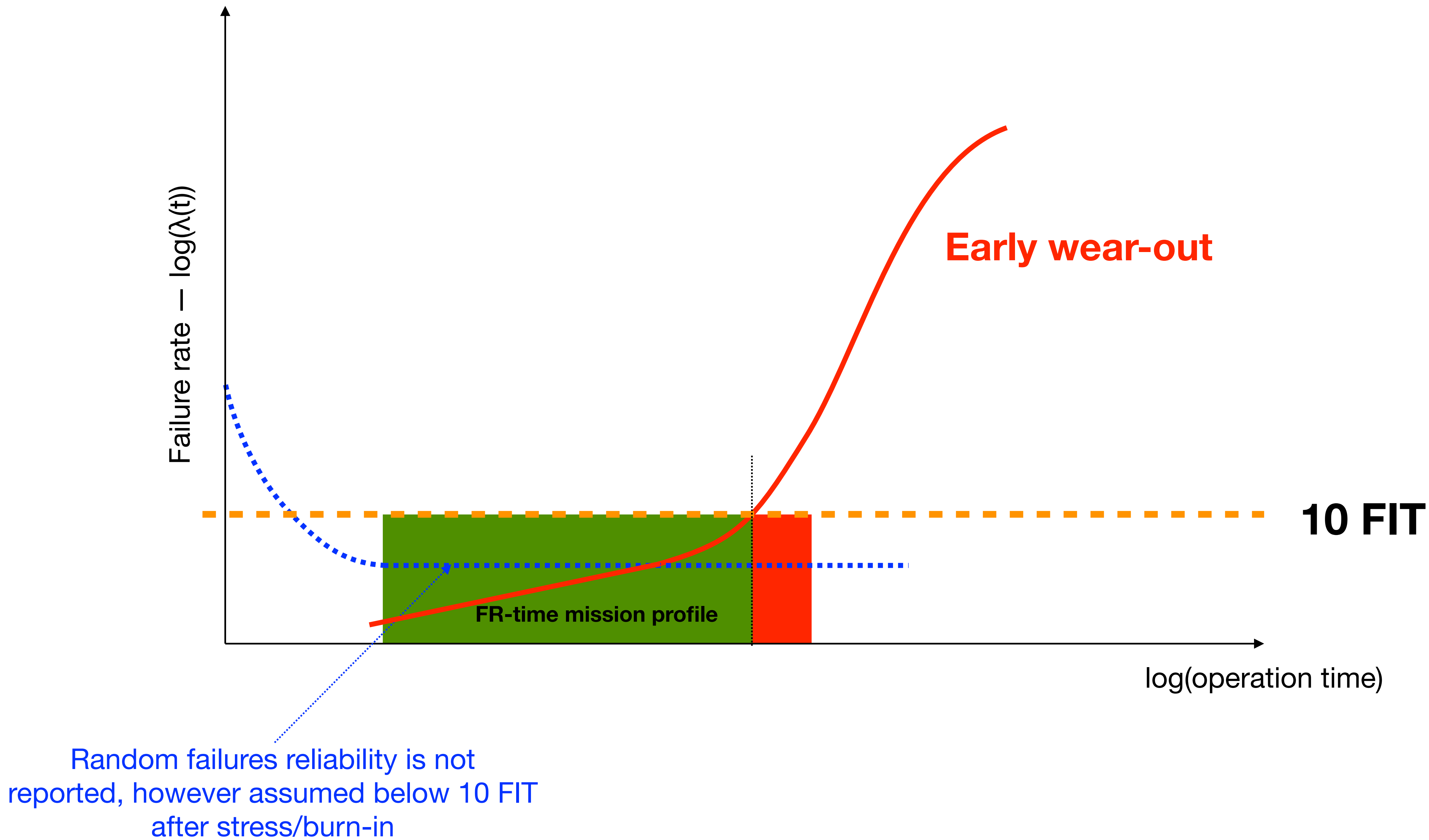
# Reliability model — failure rate

- Pay attention that **in general failure-rate λ(t) is not constant** and depends on how much time the component has survived in operation
- Failure-rate is typically measured in Failures In Time (FIT), number of failures per $10^9$ (billion) **device-hours**
  - 1 FIT = probability of failure is $10^{-9}$ / 1 hour (operation)
  - 1 FIT = probability of failure is 1 ppm / 1000 hours
  - 1 FIT = 1 failure per 1000 devices operating 1 million hours = 1 failure per 10 million devices operating 100 hours




$$\lambda(t) = \lim_{\Delta t \to 0} \frac{F(t+\Delta t) - F(t)}{(1-F(t))\Delta t} = -\frac{d \ln(1-F(t))}{dt}$$

# Reliability model — illustration



# Reliability of 850nm VCSEL

Data and model of king_3cz_01_1120 and king_3cz_01a_0521

Similar analysis of perezaranda_3cz_01b_080621_vcsel_reliability at 7.5 mA

# Reliability results (model in $T_J$)

Reliability parameters

| | | | | | |
|---|---|---|---|---|---|
| **Operation** | **Operation total time (h)** | **32000** | **Reliability model** | **Wear out Ea (eV) @ $T_J$** | 1.180 |
| | **Service life (years)** | 15 | | **Wear out n @ $T_J$** | 1.640 |
| | **Min oxide aperture diam. (um)** | 7.0 | | **TTF x%, location** | 50.0 |
| | **$I_{OP}$ (mA) max** | **7.0000** | | **Log-normal σ', ln (hours)** | 0.5 |
| | **$J_{OP}$ (kA/cm²)** | 18.20 | | **$J_0$ (kA/cm²)** | 19.50 |
| | **$J_{OP}$ (mA/um²)** | 0.18 | | **$T_{J0}$ (ºC)** | 193 |
| | **$\Delta T_{AS}$ (ºC)** | 20.0 | | **$TTF_0$ x% (hours)** | 965 |
| VCSEL model fitting | $R_{JS}$ (K/W) @ room Ts reference | 1950 | | **Arrhenius C factor (hours) @ $T_J$** | 2.200519E-08 |
| | $R_{JS}$ factor | 100 % | | **Qe** | 1.6022E-19 |
| | $R_{JS}$ (K/W) @ room Ts | 1950 | | **$K_B$** | 1.3806E-23 |
| | $R_{JS}$ room Ts (ºC) | 20.0 | | **Qe/$K_B$** | 1.1605E+04 |
| | $R_{JS}$ Exponent | 1.067 | | **ºC to Kelvin** | 273.15 |
| | $R_{JS}$ Current fitting p0 | 0.01754 | VCSEL model fitting | $P_{DIS}$ poly-fitting p11 | -0.006889 |
| | $R_{JS}$ Current fitting p1 | 0.9636 | | $P_{DIS}$ poly-fitting p02 | -5.203E-05 |
| | $P_{DIS}$ poly-fitting p00 | -0.3481 | | $P_{DIS}$ poly-fitting p21 | 0.0001612 |
| | $P_{DIS}$ poly-fitting p10 | 1.291 | | $P_{DIS}$ poly-fitting p12 | 3.641E-05 |
| | $P_{DIS}$ poly-fitting p01 | 0.01552 | | $P_{DIS}$ poly-fitting p03 | 1.736E-15 |
| | $P_{DIS}$ poly-fitting p20 | 0.05763 | | | |

- Recommended $I_{bias}$ = 7 mA for performance

$$TTF_{5FIT} = \exp\left(\mu' + \sigma' \cdot \Phi^{-1}\left(\frac{5 \cdot 32000}{1000} 10^{-9}\right)\right)$$

$$\lambda(t) = -\frac{d \ln(1 - F(t))}{dt}; \; ppm = \frac{\lambda(t) \cdot 32000}{1000}$$

Reliability result

| | Temperature profile | | | | | | | Failure rate | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Percentage** | **Operation time per Temperature (h)** | **$T_A$ (ºC)** | **$T_S$ (ºC)** | **$R_{JS}$ (K/W)** | **$P_{DIS}$ (mW)** | **$T_J$ (ºC)** | **TTF x% (hours)** | **$TTF_{5FIT}$ (hours)** | **Equivalent time in max T (hours)** | **Log-normal mu', ln (hours)** | **Failure-rate wear out (FIT)** | **Failure-rate maverick (FIT)** | **ppm** |
| **T0** | **6 %** | 1920 | **-40** | -20.0 | 1811.5 | 12.09 | 1.9 | 7.895E+11 | **61299412617** | 0.00 | 27.3947 | | | |
| **T1** | **20 %** | 6400 | **23** | 43.0 | 2296.2 | 10.82 | 67.8 | 5.199E+07 | **4036561** | 1.34 | 17.7665 | | | |
| **T2** | **65 %** | 20800 | **50** | 70.0 | 2506.1 | 10.77 | 97.0 | 2.202E+06 | **170955** | 102.86 | 14.6048 | | | |
| **T4** | **8 %** | 2560 | **100** | 120.0 | 2897.5 | 11.46 | 153.2 | 1.678E+04 | **1303** | 1661.56 | 9.7277 | $\lambda(t)$ | | |
| **T5** | **1 %** | 320 | **105** | 125.0 | 2936.8 | 11.58 | 159.0 | 1.089E+04 | **845** | 320.00 | $\mu'$ 9.2954 | | | $ppm$ |
| **Cummulative** | 100 % | **32000** | | | | | | | | $t$ **2085.76** | **9.2954** | **1625.3** | **5.0** | **52170** |

**> 10 FIT !**

# Reliability of 850nm VCSEL

Data presented in **giovane_3cz_01_080621**
Model fitting and calculations presented in perezaranda_3cz_01b_080621_vcsel_reliability and perezaranda_3cz_01_150621_vcsel_reliability_annex

# giovane_3cz_01_080621

## 850 nm 25G VCSEL Reliability

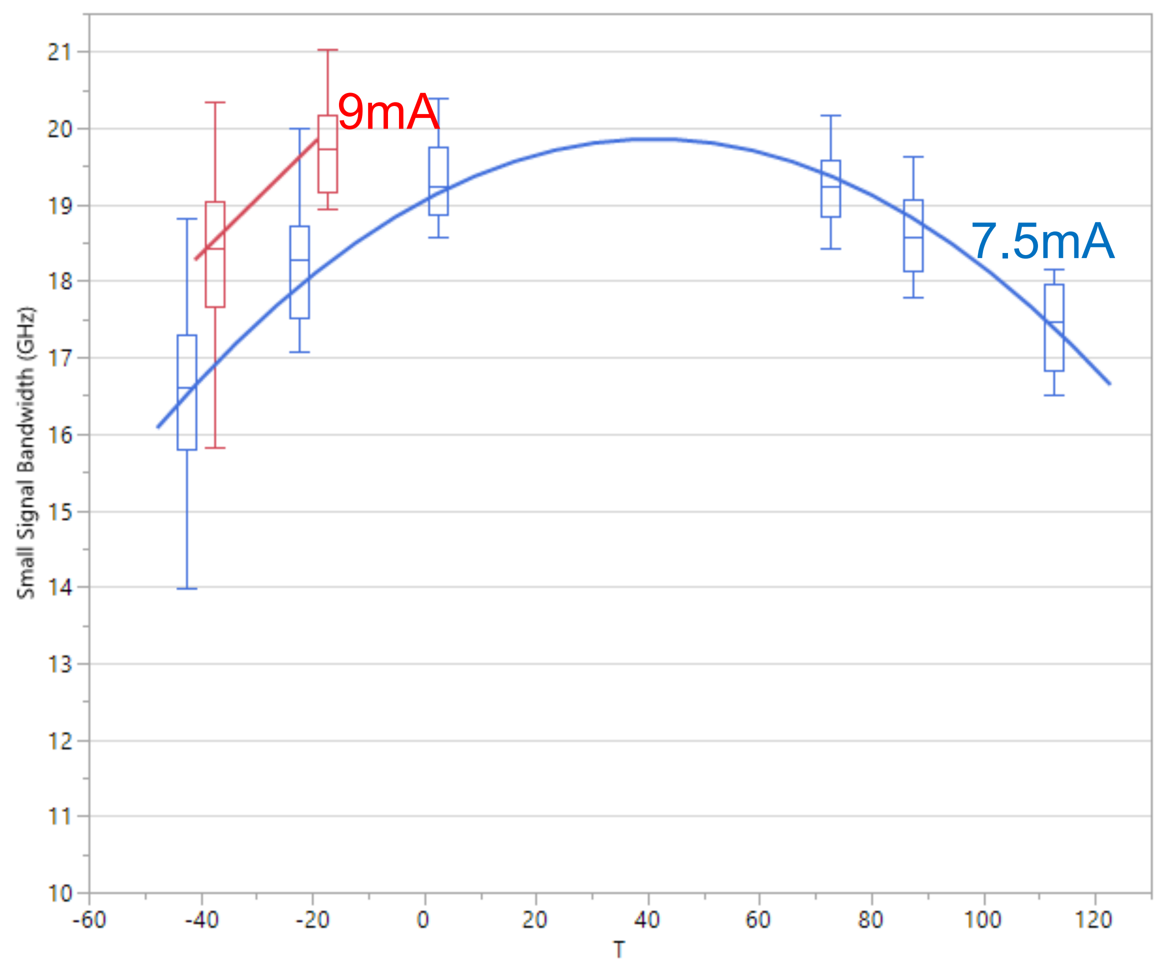
**Laura Giovane, Broadcom Inc**

IEEE 802.3cz Task Force
8 June 2021

# Performance and recommended bias

## 850nm 25G VCSEL Characterization
## Bandwidth Performance Over Temperature

- Intended for extended temperature range 0-85°C
- Recommended bias is 7.5mA and
- Small signal bandwidth exceeds 17GHz
- Bandwidth at 115°C is greater than 16GHz
- At -40°C bandwidth decay can be increased by increasing bias without concern for reliability.

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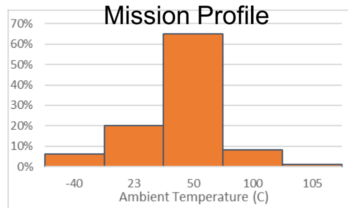
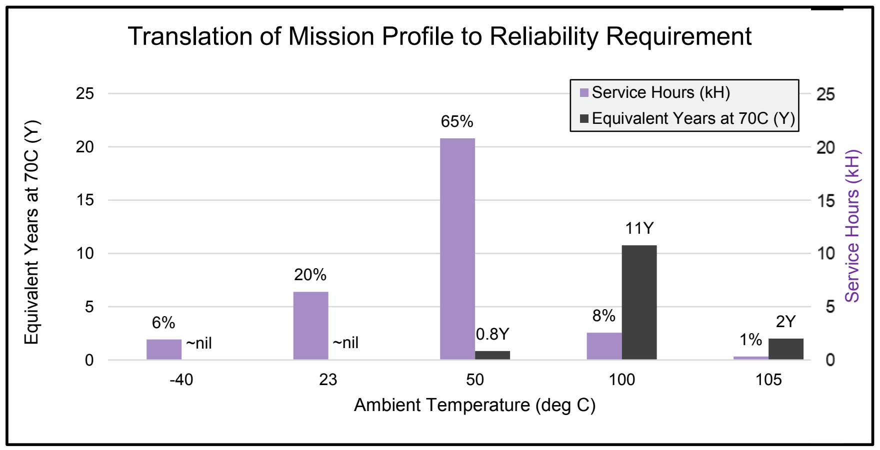
# Acceleration factors — $\Delta T_{SJ}$ constant

## 850nm 25G VCSEL Reliability Requirement

| | Data Center | Automotive |
|---|---|---|
| Ambient Temperature | 0-70C –commercial<br>0-85C –extended<br>Most of time near max temperature | Wider: -40C-105C<br>Temperature Profile |
| Service Life (VCSEL on hours) | 88kH=10Y | 32kH=3.6Y |




- 25G 850nm Datacom VCSELs are specified and designed for 10 years of continuous use (24x7x52x10=88kH) at constant substrate temperature
- Assumptions to translate automotive mission profile and service life to reliability requirement:
  - Total vehicle operating time: 32kH
  - Mission temperature profile: >90% of operating time is below 50C!
  - Acceleration model for 25G VCSEL (Ea=1.15eV)
  - VCSEL substrate is 10degC hotter than ambient
- **32kH Automotive service life/mission profile corresponds to ~13Y at 70C (substrate)**

4 |

- Acceleration factors can be calculated based on reliability model (Arrhenius's Eq for absolute temperature)
- Assumed that Ea = 1.15 eV is given in terms of $T_J$ (verbally confirmed by presenter)
- **$\Delta T_{SJ}$ = 25°C constant across $T_S$ is considered as possible cause to explain the presented results**
  - **However, GaAs $R_{TH}$ is expected to increase with $T_S$**
- **32kH Automotive mission profile corresponds to ~29Y at 70°C (substrate)**

$$AF_i = \exp\left(\frac{E_a \cdot e}{k_B}\left(\frac{1}{T_{J_{REF}}} - \frac{1}{T_{J_i}}\right)\right)$$

**Calculated $T_J$ as $\Delta T_{SJ}$ = 25°C**

| | Percentage | Operation time per Temperature (h) | $T_A$ (°C) | $T_S$ (°C) $\Delta T_{AS}$ = 20°C | $T_J$ (°C) $\Delta T_{AS}$ = 20°C $\Delta T_{SJ}$ = 25°C | Acc Factor $\Delta T_{AS}$ = 20°C | Equivalent time in $T_{REF}$ (Years), $\Delta T_{AS}$ = 20°C | $T_S$ (°C) $\Delta T_{AS}$ = 10°C | $T_J$ (°C) $\Delta T_{AS}$ = 10°C $\Delta T_{SJ}$ = 25°C | Acc Factor $\Delta T_{AS}$ = 10°C | Equivalent time in $T_{REF}$ (Years), $\Delta T_{AS}$ = 10°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{REF}$ | | | – | 70 | 95.0 | ← $T_{J_{REF}}$ | | 70 | 95.0 | ← $T_{J_{REF}}$ | |
| T0 | 6 % | 1920 | -40 | -20 | 5.0 | 0.000 | 0.00 | -30 | -5.0 | 0.000 | 0.00 |
| T1 | 20 % | 6400 | 23 | 43 | 68.0 | 0.057 | 0.04 | 33 | 58.0 | 0.017 | 0.01 |
| T2 | 65 % | 20800 | 50 | 70 | 95.0 | 1.000 | 2.38 | 60 | 85.0 | 0.363 | 0.87 |
| T3 | 8 % | 2560 | 100 | 120 | 145.0 | 76.287 | 22.36 | 110 | 135.0 | 34.903 | 10.23 |
| T4 | 1 % | 320 | 105 | 125 | 150.0 | 111.231 | 4.07 | 115 | 140.0 | 51.845 | 1.90 |
| Cumulative | 100 % | 32000 | | | | $AF_i$ | 28.85 | | | $AF_i$ | 13.01 |

**Result matches OK**

Parameters

| | |
|---|---|
| $I_{OP}$ (mA) | 7.5 |
| Ea (eV) | 1.15 |
| Qe | 1.6022E-19 |
| KB | 1.3806E-23 |
| Qe/KB | 1.1605E+04 |
| °C to Kelvin | 273.15 |
| Operation total time (h) | 32000 |

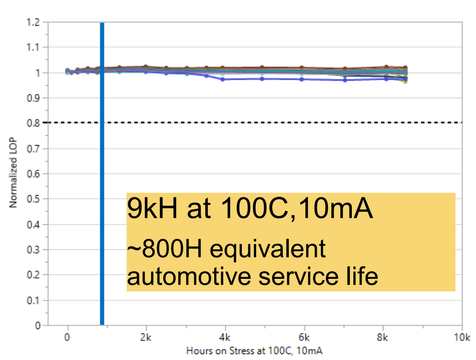
# *Ea* and *n* calculation — $\Delta T_{SJ}$, $R_{TH}$, $V_{AK}$ constants

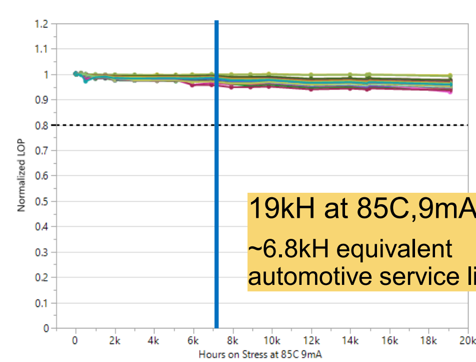
## High Temperature Operating Life

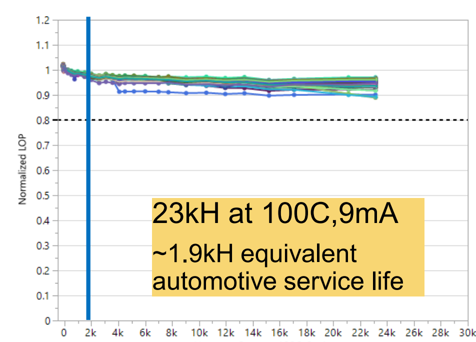
- Long-term aging (over many years) show that 850nm VCSELs are robust for automotive mission profile
  - >4000 channels with cumulative >30MH without failure
- Negligible degradation for VCSELs in stress for extended high temperature operating life after 10kH!
- 32kH mission profile/service life equivalent at 7.5mA bias shown by blue vertical line

| Temperature-Ambient | Ibias (mA) | Mission profile % | Total Time |
|---|---|---|---|
| -40°C | 7.5 | 6% | 1.9kH |
| 23°C | 7.5 | 20% | 6.4kH |
| 50°C | 7.5 | 65% | 20.8kH |
| 100°C | 7.5 | 8% | 2.6kH |
| 105°C | 7.5 | 1% | 0.3kH |

Mission profile/service life

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- Using VCSEL reliability model, we can calculate *Ea* and *n* from reported data
- $R_{TH}$ is considered constant with $T_S$
- $V_{AK}$ is considered constant with $I_{BIAS}$ and $T_S$
- $P_{DIS} >> P_{OPTICAL}$
- **Calculated *Ea* = 1.146 eV vs 1.15 eV: very good matching!**
  - However, $V_{AK}$ and $R_{TH}$ should not be considered constants
- **Calculated n = 8.2 >> 1.64 of King 850nm 25G VCSEL**
  - Possible root cause may be current exponent is accounting aging effects due to temperature, because the considered assumptions.

$$T_J = T_S + \frac{I_{BIAS}(mA)}{7.5}\cdot \Delta T_{SJ@7.5mA}$$

$$E_a = \frac{\frac{k_B}{e}\cdot \ln\left(\frac{TTF_1}{TTF_0}\right)}{\frac{1}{T_{J1}} - \frac{1}{T_{J0}}} \quad for\ I_1 = I_0$$

$$n = -\frac{\ln\left(\frac{TTF_1}{TTF_0}\right)}{\ln\left(\frac{I_1}{I_0}\right)} \quad for\ T_{J1} = T_{J0}$$

Parameters

| | |
|---|---|
| Qe | 1.6022E-19 |
| KB | 1.3806E-23 |
| Qe/KB | 1.1605E+04 |
| °C to Kelvin | 273.15 |

Ea and N consistency

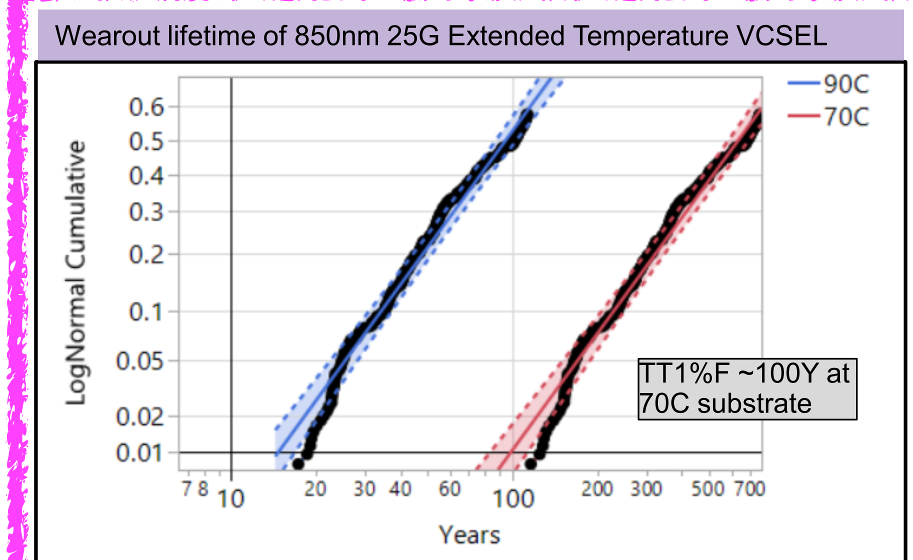
| Experiment | Ts (°C) | IBIAS (mA) | TJ (°C) $\Delta T_{SJ}$ = 25°C @ 7.5 mA | Equiv. Time (h) | Estim. Ea (eV) Using 2, 3 | Estim. N Using 1,3 |
|---|---|---|---|---|---|---|
| 1 | 100 | 10 | 133.3 | 800 | | |
| 2 | 85 | 9 | 115.0 | 6800 | | |
| 3 | 100 | 9 | 130.0 | 1900 | 1.146 | 8.210 |

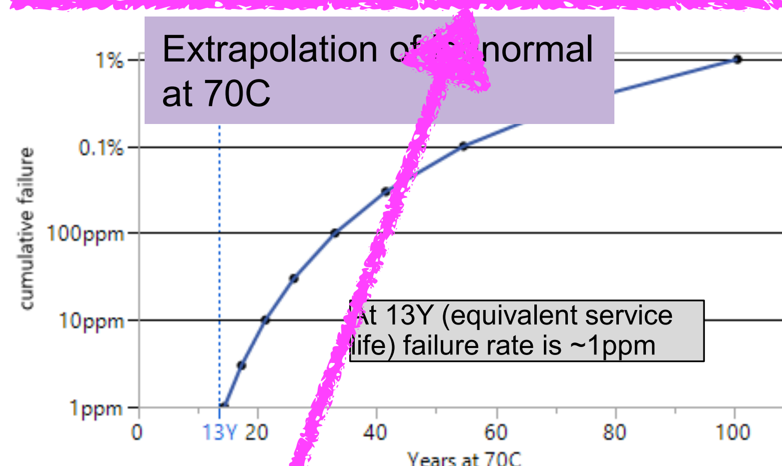
# Lognormal unreliability function fitting

## Extended Temperature 25G 850nm VCSEL Characteristic

Wearout Lifetime

- Equivalent of ~13Y of life at 70C (substrate) required for automotive application
- Extended Temperature Datacom VCSEL specified at >10Y at 85C and >40Y wearout life at 70C
  - Characteristic TT1%F 25G VCSEL is ~100 Years at 70C (substrate)
  - Extrapolation shows low-level cumulative failure at 13Y, 70C that corresponds to automotive mission life corresponds to <1ppm
- 850 nm 25G VCSELs are capable of performing in automotive application for duration of service life

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$$C = TTF_{x\%} \cdot I_0^{\,n} \cdot \exp\left( -\frac{E_a \cdot e}{k_B \cdot T_{J_0}} \right)$$

$$\sigma' = \frac{\ln\left(TTF_{1\%}\right) - \ln\left(TTF_{50\%}\right)}{\Phi^{-1}\left(0.01\right)} \simeq 0.8$$

# Reliability results

Reliability parameters

| Operation | Operation total time (h) | 32000 | Reliability model | Wear out Ea (eV) @ $T_J$ | 1.150 |
|---|---|---|---|---|---|
| | Service life (years) | 15 | | Wear out n @ $T_J$ | 8.210 |
| | | | | TTF x%, location | 1.0 |
| | $I_{OP}$ (mA) max | 7.5000 | | Log-normal σ', ln (hours) | 0.8 |
| | $\Delta T_{AS}$ (ºC) | 20.00 | | $I_0$ (mA) | 7.5 |
| | | | | $T_{I0}$ (ºC) | 95.0 |
| | | | | $TTF_0$ x% (hours) | 873600 |
| VCSEL model fitting | $\Delta T_{SJ}$ (ºC) @ 7.5mA | 25.0 | | Arrhenius C factor (hours) @ $T_J$ | 2.413444E-03 |
| | $I_{FIT}$ (mA) | 7.5 | | Qe | 1.6022E-19 |
| | | | | $K_B$ | 1.3806E-23 |
| | | | | $Qe/K_B$ | 1.1605E+04 |
| | | | | ºC to Kelvin | 273.15 |

Ea

n can take any value w/o effect because reference $I_0 = I_{OP}$

TTF for 1%

$\sigma'$ calculated from $TTF_{50\%}$ and $TTF_{1\%}$

$I_0 = I_{OP} = 7.5$ mA

$TTF_{1\%}$ ~100 years for 70ºC substrate

$$C = TTF_{x\%} \cdot I_0^{\,n} \cdot \exp\left(-\frac{E_a \cdot e}{k_B \cdot T_{J_0}}\right)$$

$$TTF_{5FIT} = \exp\left(\mu' + \sigma' \cdot \Phi^{-1}\left(\frac{5 \cdot 32000}{1000} 10^{-9}\right)\right)$$

$$T_J = T_S + \frac{I_{BIAS}(mA)}{7.5} \cdot \Delta T_{SJ@7.5mA}$$

$$\lambda(t) = -\frac{d\ln(1-F(t))}{dt};\ ppm = \frac{\lambda(t) \cdot 32000}{1000}$$

Reliability result

| | Temperature profile | | | | | Failure rate | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Percentage | Operation time per Temperature (h) | $T_A$ (ºC) | $T_S$ (ºC) | $T_J$ (ºC) | TTF x% (hours) | $TTF_{5\ FIT}$ (hours) | Equivalent time in max T (hours) | Log-normal mu', ln (hours) | Failure-rate wear out (FIT) | Failure-rate maverick (FIT) | ppm |
| T0 | 6 % | 1920 | -40 | -20.00 | 5.0 | 1.084E+11 | 11684618447 | 0.00 | 27.2706 | | | |
| T1 | 20 % | 6400 | 23 | 43.00 | 68.0 | 1.539E+07 | 1658406 | 3.27 | 18.4104 | | | |
| T2 | 65 % | 20800 | 50 | 70.00 | 95.0 | 8.736E+05 | 94131 | 187.00 | 15.5415 | | | |
| T3 | 8 % | 2560 | 100 | 120.00 | 145.0 | 1.145E+04 | 1234 | 1755.75 | 11.2070 | | | |
| T4 | 1 % | 320 | 105 | 125.00 | 150.0 | 7.854E+03 | 846 | 320.00 | 10.8298 | | | |
| Cummulative | 100 % | 32000 | | | | | | $t$ 2266.01 | $\mu'$ 10.8298 | $\lambda(t)$ 118.4411 | 5.0 | $ppm$ 3950 |

**> 10 FIT !**

# Reliability of 850nm VCSEL

Data and model presented in **Hoser_3dh_220824**

# 850 and 910nm VCSELs for POF Automotive Links

Mirko Hoser, II-VI Inc.

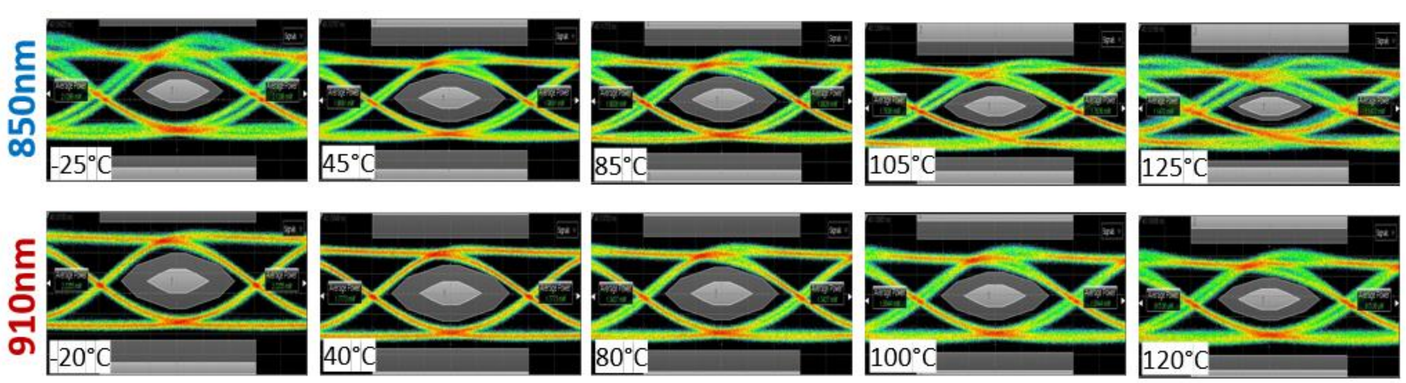
802.3dh Task Force Plenary Meeting

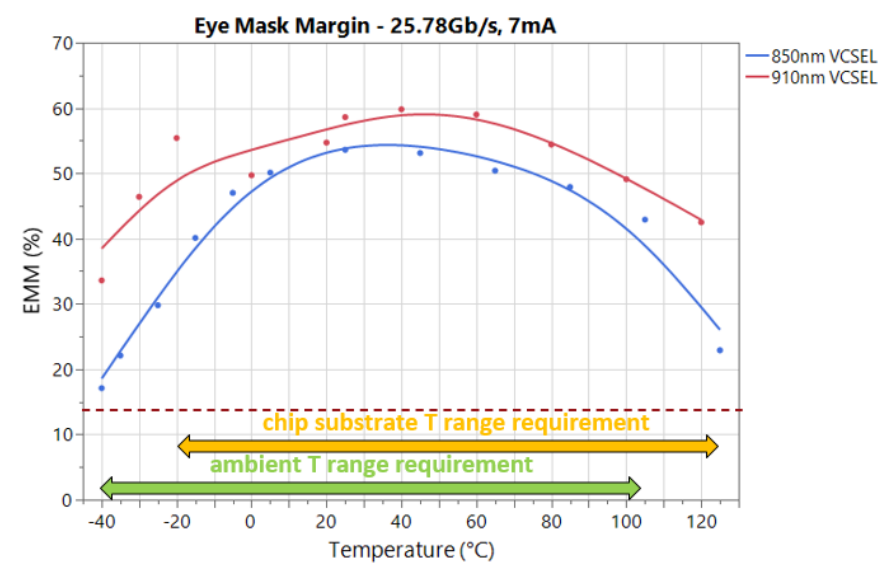
August 24th, 2022

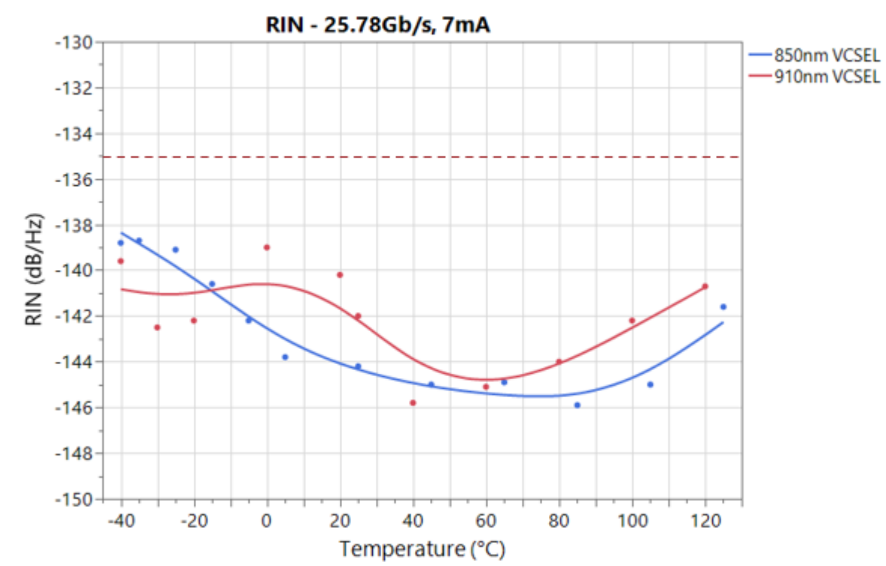
# Performance and recommended bias

## 850/910 nm VCSEL – Large Signal Performance

- **850 and 910nm 28G NRZ VCSELs tested**
- **Test setup:**
  - BPG -> Bias-Tee -> Probe -> VCSEL -> OE module
  - no DSP, no impedance matching etc.
  - 25.78 Gb/s, 7mA
- **good RF Performance over whole automotive temperature range demonstrated:**
  - EMM > 20%
  - RIN < -138 dB/Hz



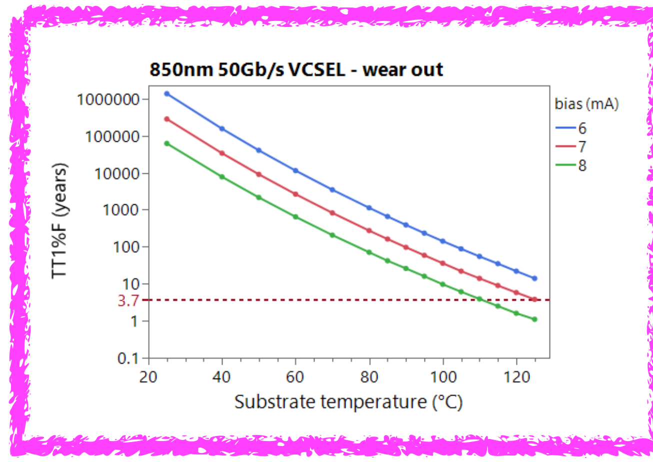



# *Ea* and *n* fitting (Arrhenius's equation in $T_S$)

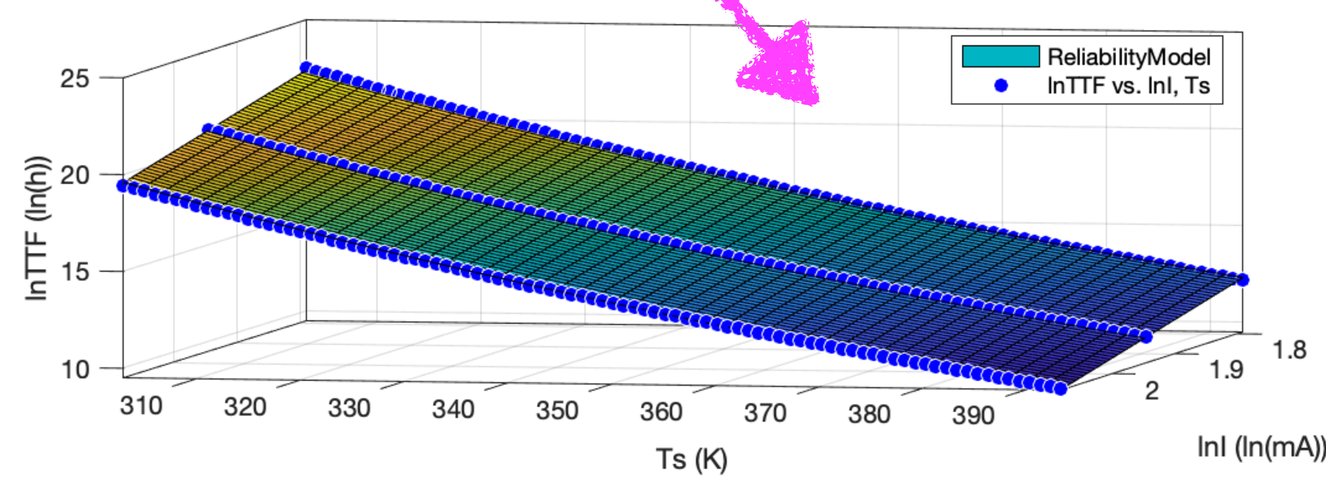
## 850nm VCSEL – Wear-Out Lifetime

- **Accelerated Lifetime Tests at 9mA and 125°C**
  - conservative MFT >9khrs
  - >340h TTFF release criteria for Datacom (TT1%F>10years at 70°C/8mA)
- **TT1%F at different operation conditions calculated by aging model (Ea=1.3eV)**
  - TT1%F > 3.7 years or 1.1 years until 1ppm cumulated failures at 7mA and 105°C ambient T (ΔT=20°C)
  - 1 ppm cumulated failures after 28.8 years at 7mA and 70°C ambient T

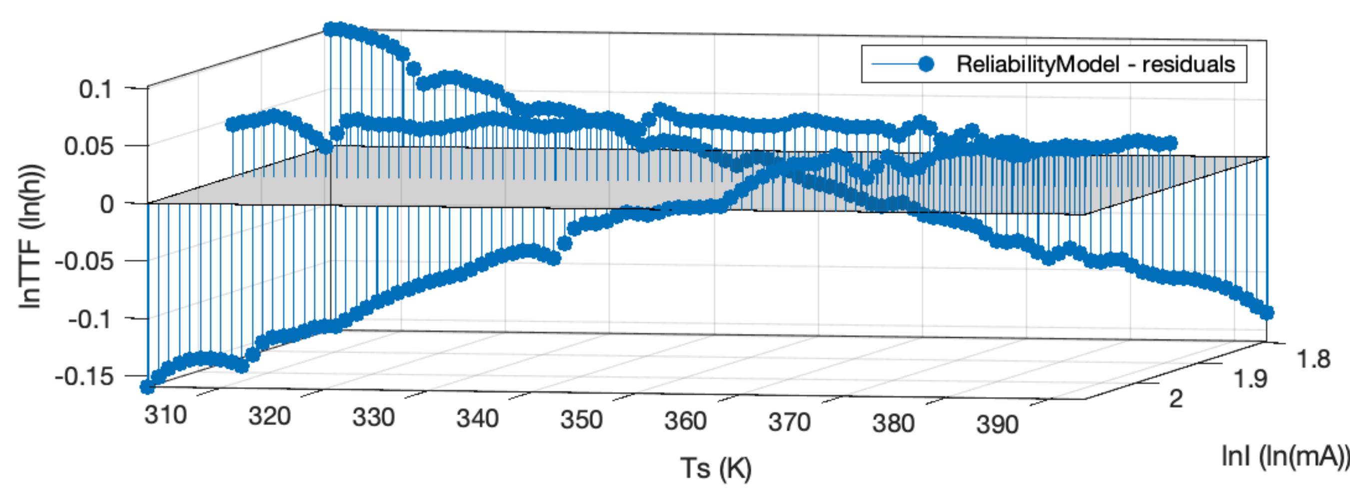
⇒ **automotive requirement of > 3.7 years operation demonstrated**




| ambient T (°C) | substrate T (°C) | time to 1ppm cumulated failures at 7mA |
|---|---|---|
| -40 | -20 | >>1k years |
| 23 | 43 | >>1k years |
| 70 | 90 | 28.8 |
| 100 | 120 | 1.7 |
| 105 | 125 | 1.1 |




$$\ln\left(TTF_{x\%}\right)=\ln\left(C\right)-n\cdot\ln\left(I\right)+\frac{E_a\cdot e}{k_B}\cdot\frac{1}{T_S}$$

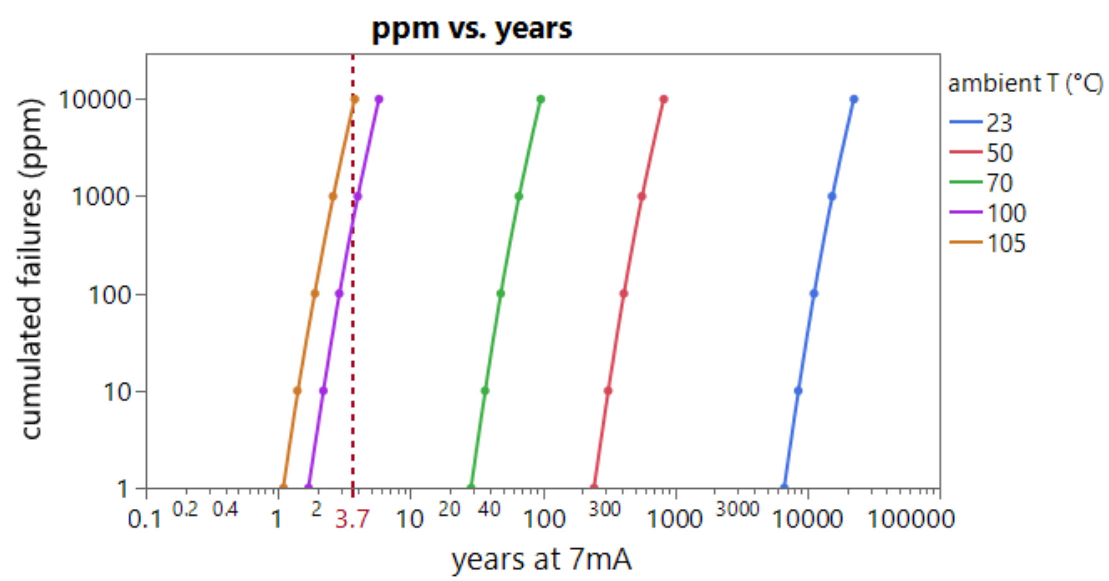



- $E_a$ = 1.15 eV < 1.3 eV
- n = 9.8
  - n is very high. Model is at $T_S$ vs $T_J$, so part of the self-heating effect on aging is being accounted by current exponent instead activation energy. $R_{th}$ and $V_{AK}$ depends on $T_S$.

# Lognormal unreliability function fitting

## Appendix: 850nm VCSEL – Wear-Out Lifetime

- **Lognormal extrapolation for 7mA and different ambient T**




$$\ln\left(TTF_{x\%}\right) = \mu' + \sigma' \cdot \Phi^{-1}\left(\frac{x}{100}\right)$$

$$TTF_{1\%} = \exp\left(\mu' + \sigma' \cdot \Phi^{-1}\left(0.01\right)\right)$$

$$E_a = \frac{\mu_1 - \mu_0}{\frac{e}{k_B}\left(\frac{1}{T_{S_1}} - \frac{1}{T_{S_0}}\right)}$$

Lognormal fitting

| $T_A$ (°C) | 23 | 50 | 70.0 | 100 | 105 |
|---|---|---|---|---|---|
| Location (μ') | 20.2529 | 16.9437 | 14.8100 | 12.0062 | 11.6276 |
| Shape (σ') | 0.5015 | 0.5016 | 0.5037 | 0.5063 | 0.5209 |
| $E_a$ (eV) | | 1.1457 | 1.1457 | 1.1471 | 1.1409 |
| $TTF_{1\%}$ (hours) | 194561592 | 7108409 | 837419 | 50435 | 33383 |

# Reliability results

Reliability parameters

| Operation | Operation total time (h) | 32000 | Reliability model | Wear out Ea (eV) @ $T_S$ | 1.15 |
|---|---|---|---|---|---|
| | Service life (years) | 15 | | Wear out n @ $T_S$ | 9.8 |
| | $I_{OP}$ (mA) | 7.0000 | | TTF x%, location | 1.0 |
| | $\Delta T_{AS}$ (ºC) | 20.0 | | Log-normal σ', ln (hours) | 0.52 |
| | | | | $I_0$ (mA) | 7.00 |
| | | | | $T_{S0}$ (ºC) | 125 |
| | | | | $TTF_0$ x% (hours) | 33383 |
| | | | | Arrhenius C factor (hours) @ $T_S$ | 1.546241E-02 |
| | | | | Qe | 1.6022E-19 |
| | | | | $K_B$ | 1.3806E-23 |
| | | | | Qe/$K_B$ | 1.1605E+04 |
| | | | | ºC to Kelvin | 273.15 |

Reliability result

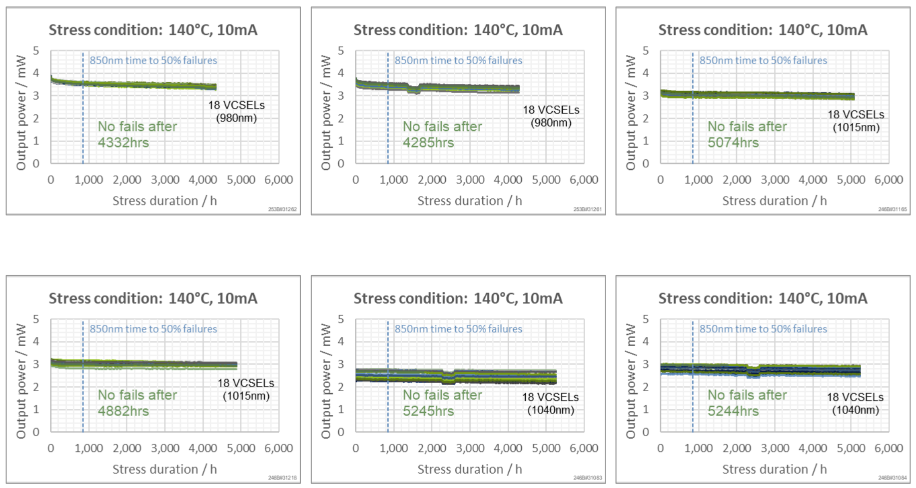
| | Temperature profile | | | | Failure rate | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Percentage | Operation time per Temperature (h) | $T_A$ (ºC) | $T_S$ (ºC) | TTF x% (hours) | $TTF_{5\ FIT}$ (hours) | Equivalent time in max T (hours) | Log-normal mu', ln (hours) | Failure-rate wear out (FIT) | Failure-rate maverick (FIT) | ppm |
| **T0** | **6 %** | 1920 | **-40** | -20.0 | 7.861E+12 | 2050349842825 | 0.00 | 30.9047 | | | |
| **T1** | **20 %** | 6400 | **23** | 43.0 | 2.063E+08 | 53817696 | 1.04 | 20.3567 | | | |
| **T2** | **65 %** | 20800 | **50** | 70.0 | 7.349E+06 | 1916870 | 94.49 | 17.0218 | | | |
| **T4** | **8 %** | 2560 | **100** | 120.0 | 5.122E+04 | 13360 | 1668.61 | 12.0556 | | | |
| **T5** | **1 %** | 320 | **105** | 125.0 | 3.338E+04 | 8708 | 320.00 | 11.6276 | | | |
| **Cummulative** | 100 % | **32000** | | | | | **2084.13** | **11.6276** | **0.0** | **5.0** | **160.00** |

**Requirement is met!**

# Wear-out reliability comparison

# Wear-out reliability: 850nm vs 980 nm comparison

## 980nm versus 850nm 25G VCSEL design wear out reliability at 140°C, 10mA stress




**850nm VCSEL**

- Time to 50% fails = 853hrs @ 140°C, 10mA

**Long wavelength VCSEL**

- No wearout fails so far

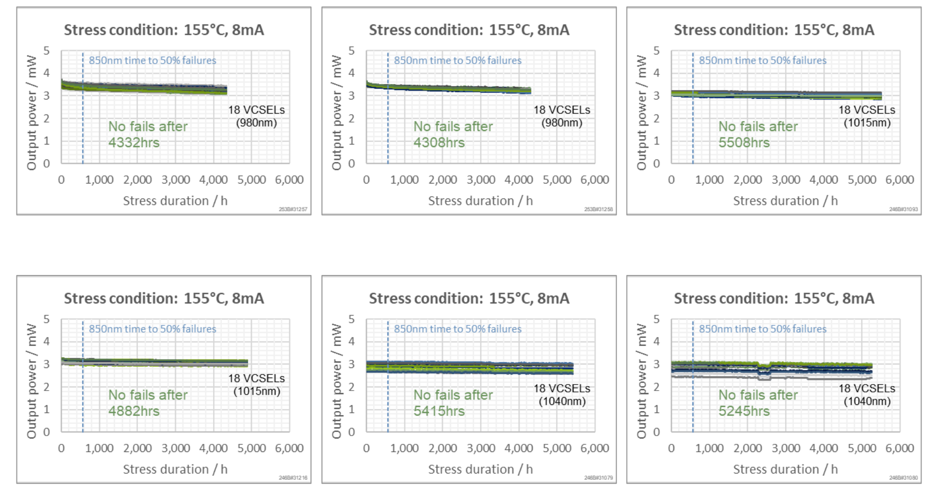
980nm endurance advantage already **>5x**

*Stress condition: 140 ℃ chip backside (substrate) temperature, 10mA continuous wave laser current*
*Every 24h the VCSEL is cooled down to ~40 ℃ and the output power at 7mA drive current is recorded*

TRUMPF



## 980nm versus 850nm 25G VCSEL design wear out reliability at 155°C, 8mA stress




**850nm VCSEL**

- Time to 50% fails = 561hrs @ 155°C, 8mA

**Long wavelength VCSEL**

- No wearout fails so far

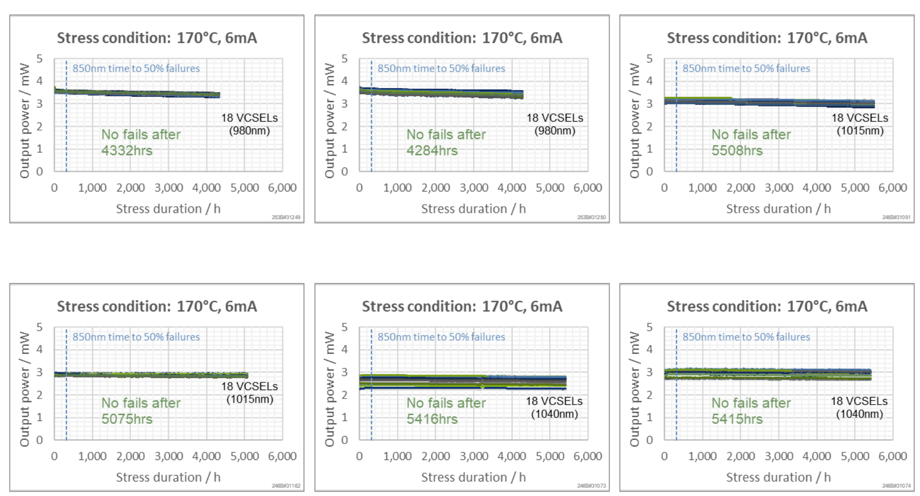
980nm endurance advantage already **>9x**

*Stress condition: 155 ℃ chip backside (substrate) temperature, 8mA continuous wave laser current*
*Every 24h the VCSEL is cooled down to ~40 ℃ and the output power at 7mA drive current is recorded*

TRUMPF



## 980nm versus 850nm 25G VCSEL design wear out reliability at 170°C, 6mA stress




**850nm VCSEL**

- Time to 50% fails = 307hrs @ 170°C, 6mA

**Long wavelength VCSEL**

- No wearout fails so far

980nm endurance advantage already **>>10x**

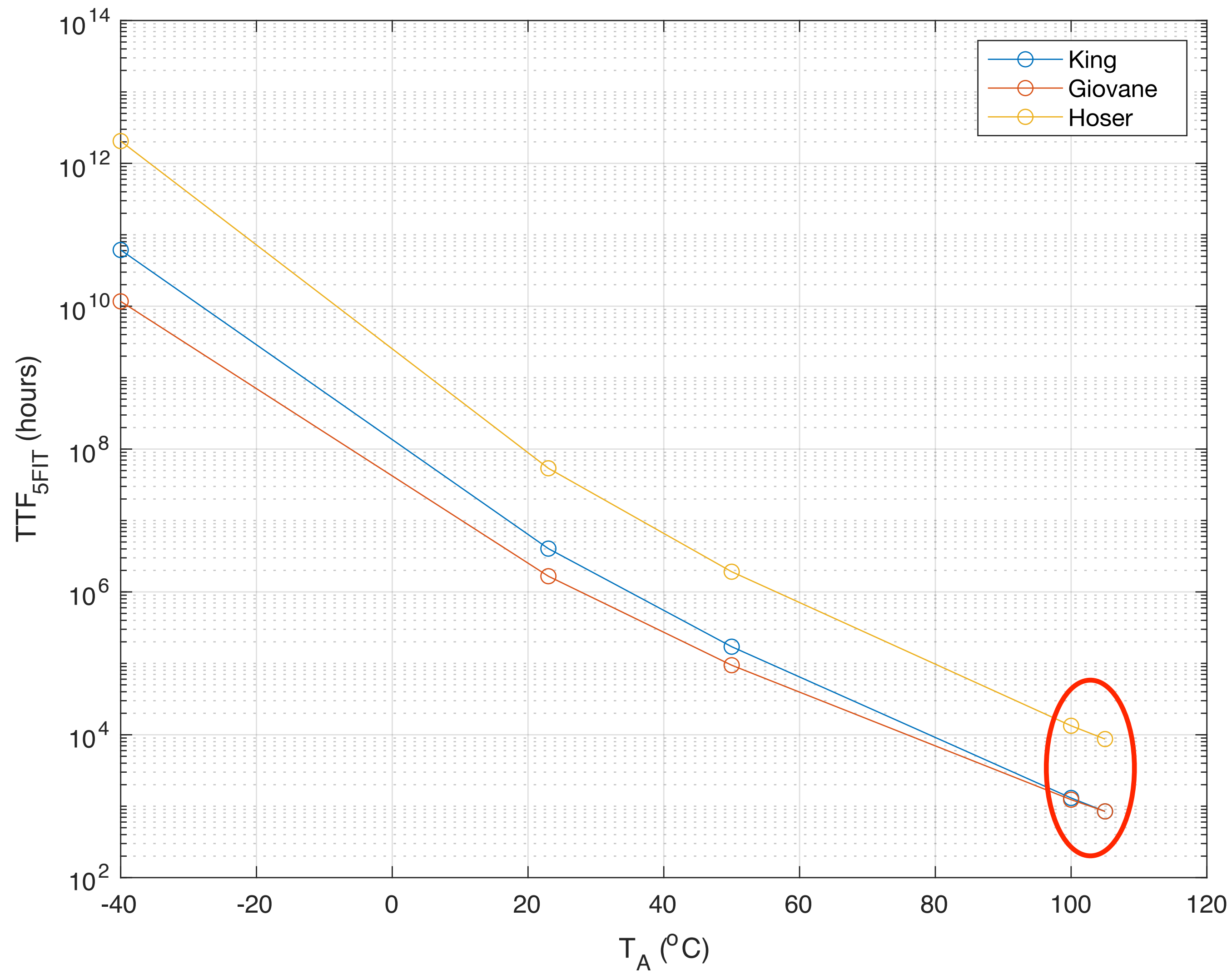
*Stress condition: 170 ℃ chip backside (substrate) temperature, 6mA continuous wave laser current*
*Every 24h the VCSEL is cooled down to ~40 ℃ and the output power at 7mA drive current is recorded*

TRUMPF

# Wear-out reliability: 850nm comparison

Reliability comparison —5 FIT

| $T_A$ (ºC) | King $TTF_{5\ FIT}$ (hours) | Giovane $TTF_{5\ FIT}$ (hours) | Hoser $TTF_{5\ FIT}$ (hours) | Giovane / King ratio | Hoser / King ratio |
|---|---|---|---|---|---|
| **-40** | 61299412617 | 11684618447 | 2050349842825 | 0.191 | 33.448 |
| **23** | 4036561 | 1658406 | 53817696 | 0.411 | 13.333 |
| **50** | 170955 | 94131 | 1916870 | 0.551 | 11.213 |
| **100** | 1303 | 1234 | 13360 | 0.947 | 10.257 |
| **105** | 845 | 846 | 8708 | 1.001 | 10.300 |




**Hoser shows 1 order of magnitude better wear-out reliability**

**Data cross-check is suggested**

# Conclusions

- Performance measurements of 3 different 850nm VCSEL devices have been reported and compared vs 980nm VCSEL
- Wear-out reliability according an automotive mission profile of 3 different 850nm VCSELs has been reported. Comparison has also been reported
- The conclusions did not change with respect to 802.3cz: 980nm is the right wavelength for the considered mission profile

- Facts:
  - Functional and environmental requirements are the same: EEE, OAM, temperature range
  - Link budget is very similar: connectors insertion loss, aging, environmental conditions
  - Physical laws, test results and reliability of VCSELs are the same with OM3 and GIPOF

- **If we do changes in components for .3dh wrt .3cz that DO NOT rely on GIPOF itself (i.e. the reason behind .3dh), confusion will be created in the market that will affect the success of both standards**

Thank you