



# CWDM-Based Radiation Tolerant High-Speed Optical Links

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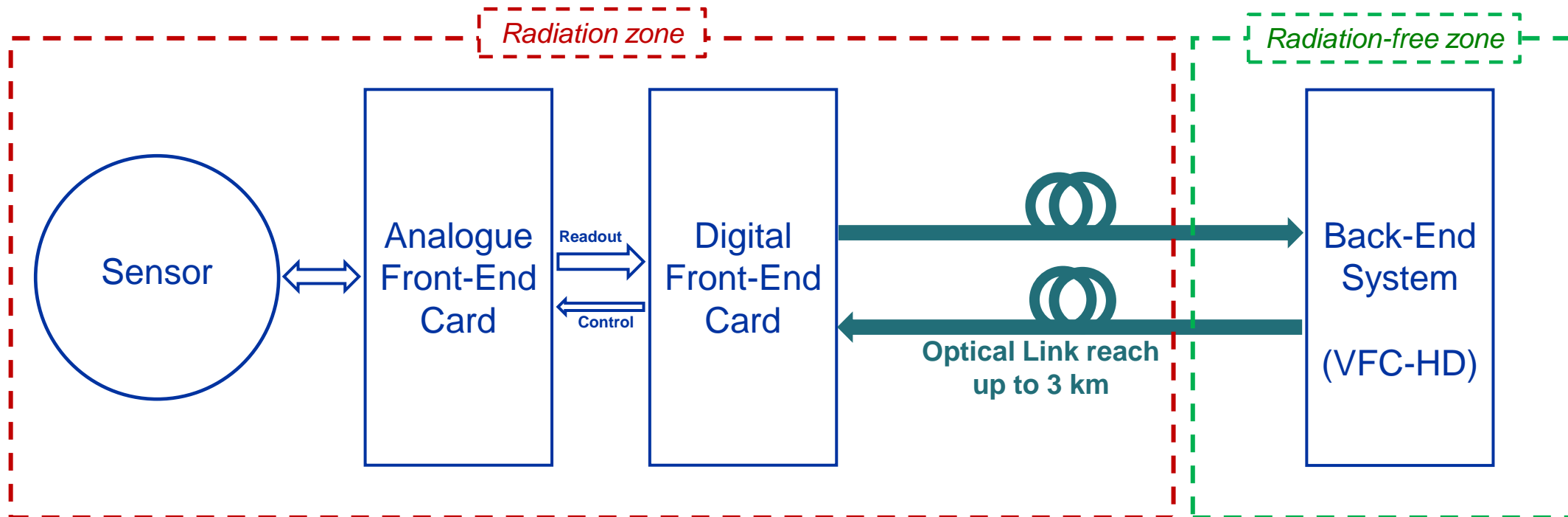
CERN EP-ESE-BE

3<sup>rd</sup> October 2024

- CWDM-Link Project
- Transmitter qualification requirements
- Transmitter qualification procedure
  - Neutron irradiation tests
  - Gamma irradiation tests
  - Temperature tests
  - GBLD Categorization

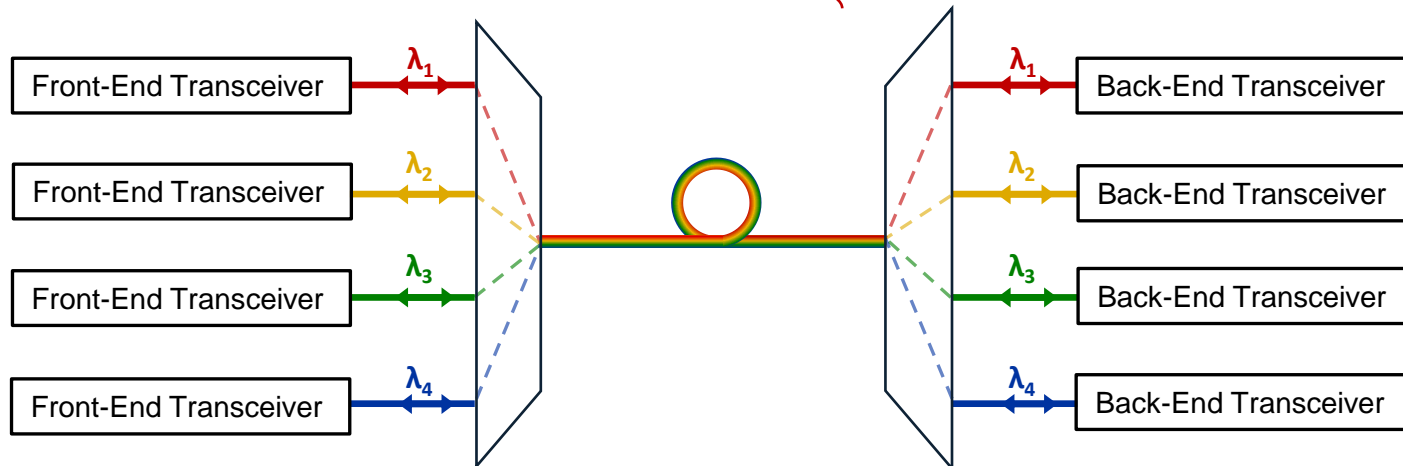
The Beam Instrumentation Group (SY-BI) is moving towards a new readout solution which optical link requires:

- An increased upstream (Front-End to Back-End) data rate up to 40 Gbps
- To use only the existent infrastructure (No additional optical fibers)

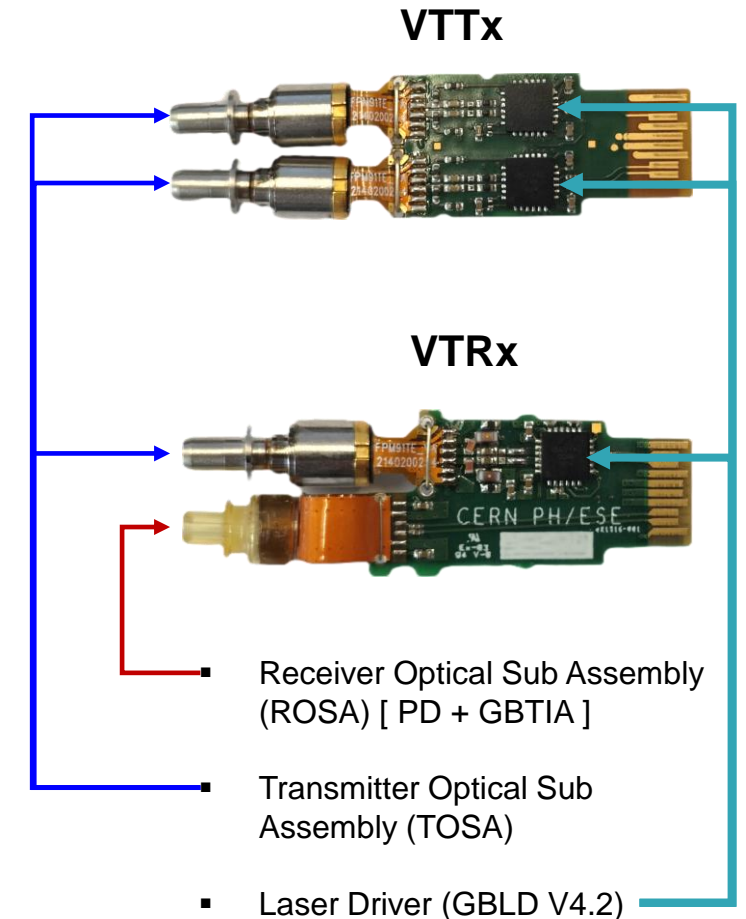


The solution is the implementation of the Coarse Wavelength Division Multiplexing (CWDM) technology based on VTRx/VTTx modules.

*Radiation zone*

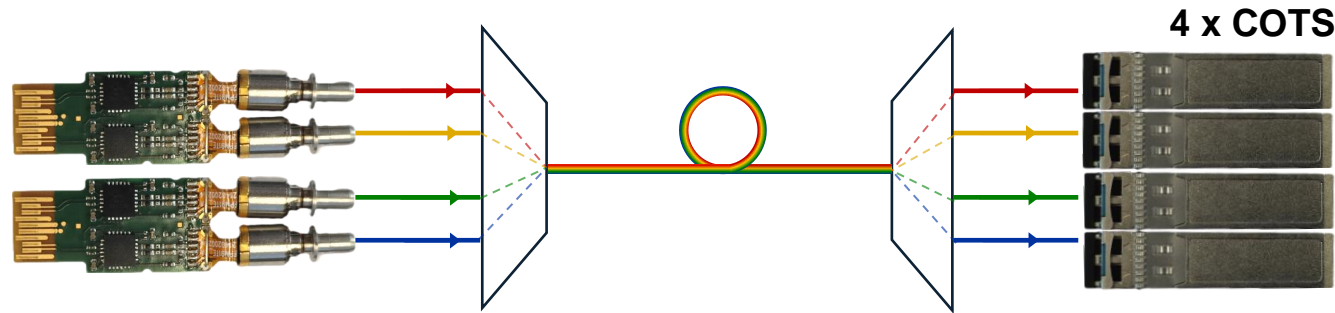


- The data rate per fiber increases proportionally to the number of channel multiplexed
- The wavelengths of the lasers are different and spaced according ITU Standard G694.2 : **1271/1291/1311/1331 nm**



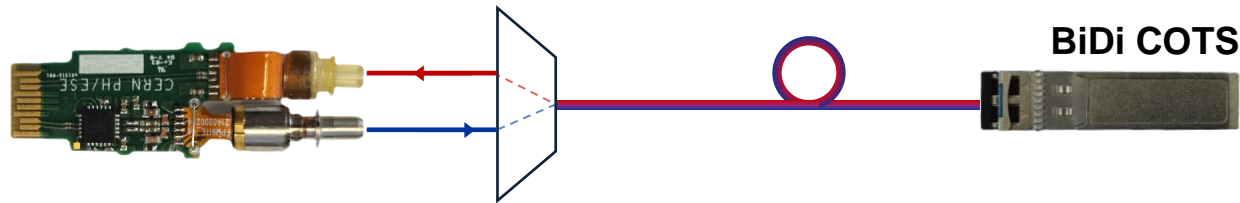
Two designs have been proposed to meet the different specifications:

## 1) CWDM 4x1 VTTx-Based



Specification	Min	Typ	Max	Unit
<b>Optical Link</b>				
BitRate (UpLink)	4.8	10	10	Gb/s
<b>Radiation tolerance</b>				
Total Ionising Dose			10	kGy
Total Hadron Fluence			$10^{12}$	$n \cdot cm^{-2}$
<b>Temperature ranges</b>				
CWDM Front-End	-5	+25	+60	°C

## 2) CWDM 2x1 VTRx-Based



Specification	Min	Typ	Max	Unit
<b>Optical Link</b>				
BitRate (UpLink)	-	4.8	4.8	Gb/s
BitRate (DownLink)	2.56	4.8	4.8	Gb/s
<b>Radiation tolerance</b>				
Total Ionising Dose			10	kGy
Total Hadron Fluence			$5 \times 10^{14}$	$n \cdot cm^{-2}$
<b>Temperature ranges</b>				
CWDM Front-End	-5	+25	+60	°C

The project is approaching the production phase. Before production, components need to be qualified.

- Assembly qualification for the ROSA
- TOSA Qualification procedure requirements:
  - 1) Power margin > 0
  - 2) Wavelength shift within CWDM MUX Passband

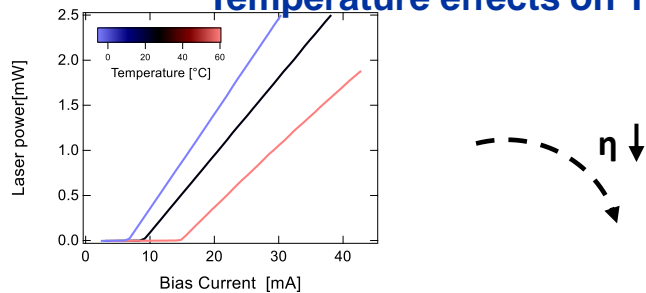
## 1) Power margin > 0

		CWDM <sub>2x1</sub>	CWDM <sub>4x1</sub>
<b>Power budget</b>	Tx OMA <sub>Min</sub>	-1 dBm	-1 dBm
	Rx Sensitivity <sub>Max</sub>	-12.6 dBm	-12.6 dBm
<b>Attenuation sources</b>	Insertion losses <sub>Max</sub>	2 dB	2 dB
	Fiber attenuation <sub>Max</sub>	1.2 dB	1.2 dB
	Fiber radiation penalty <sub>Max</sub>	1 dB	1 dB
	MUX attenuation <sub>Max</sub>	2 dB	3.8 dB
	Link penalties <sub>Max</sub> [Gb/s]	1.2 dB	2 dB
<b>Power margin</b>		4.2 dB	1.6 dB

A positive power margin ensures the transmitted signal, despite attenuation of the link, reaches the receiver with a power amplitude above its sensitivity.

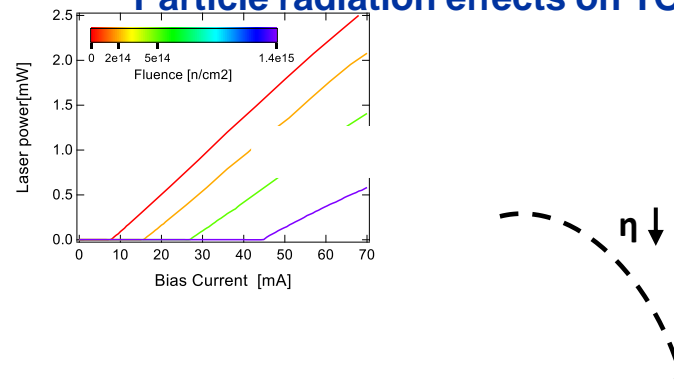
The list does not consider the degradation of the transmitter due to temperature variations and radiation damage, defined as **Tx Penalties**

Temperature effects on TOSA



---→ I<sub>Th</sub>↑

Particle radiation effects on TOSA



---→ I<sub>Th</sub>↑

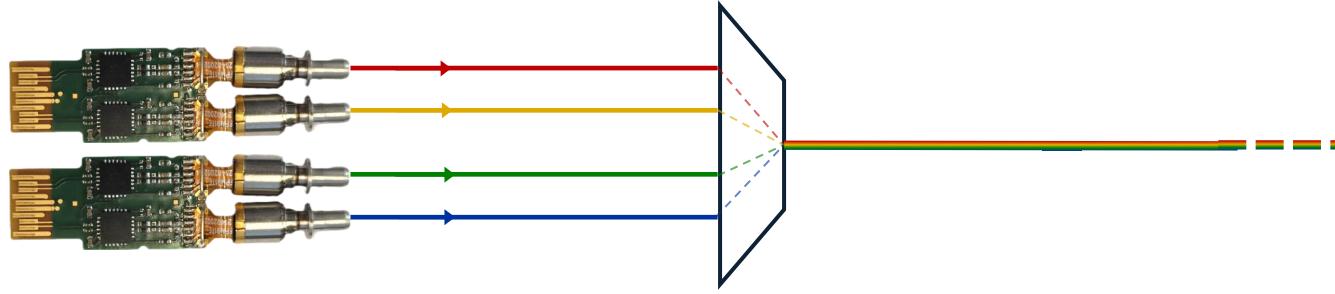
**Tx Penalties(F,T) < Power Margin**



**Tx Penalties<sub>(CWDM 4x1)</sub> (F,T) < 1.6 dB**

**Tx Penalties<sub>(CWDM 2x1)</sub> (F,T) < 4.2 dB**

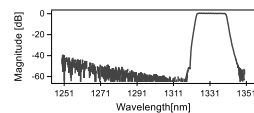
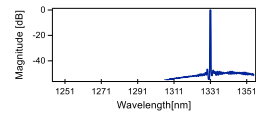
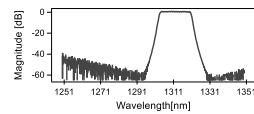
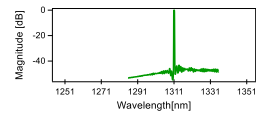
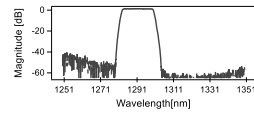
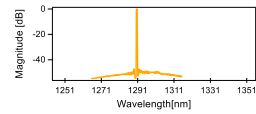
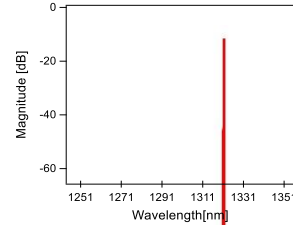
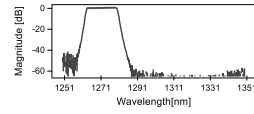
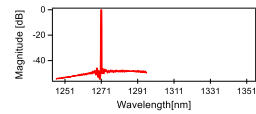
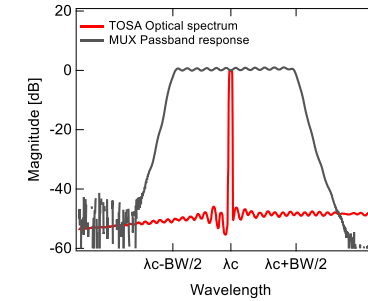
## 2) Wavelength shift within CWDM Passband



TOSAs Optical Spectrum

MUX Channels passband

Optical Spectrum @ MUX Output



$$-BW_{MUX}/2 < \lambda_{TOSA}(F,T) < BW_{MUX}/2$$



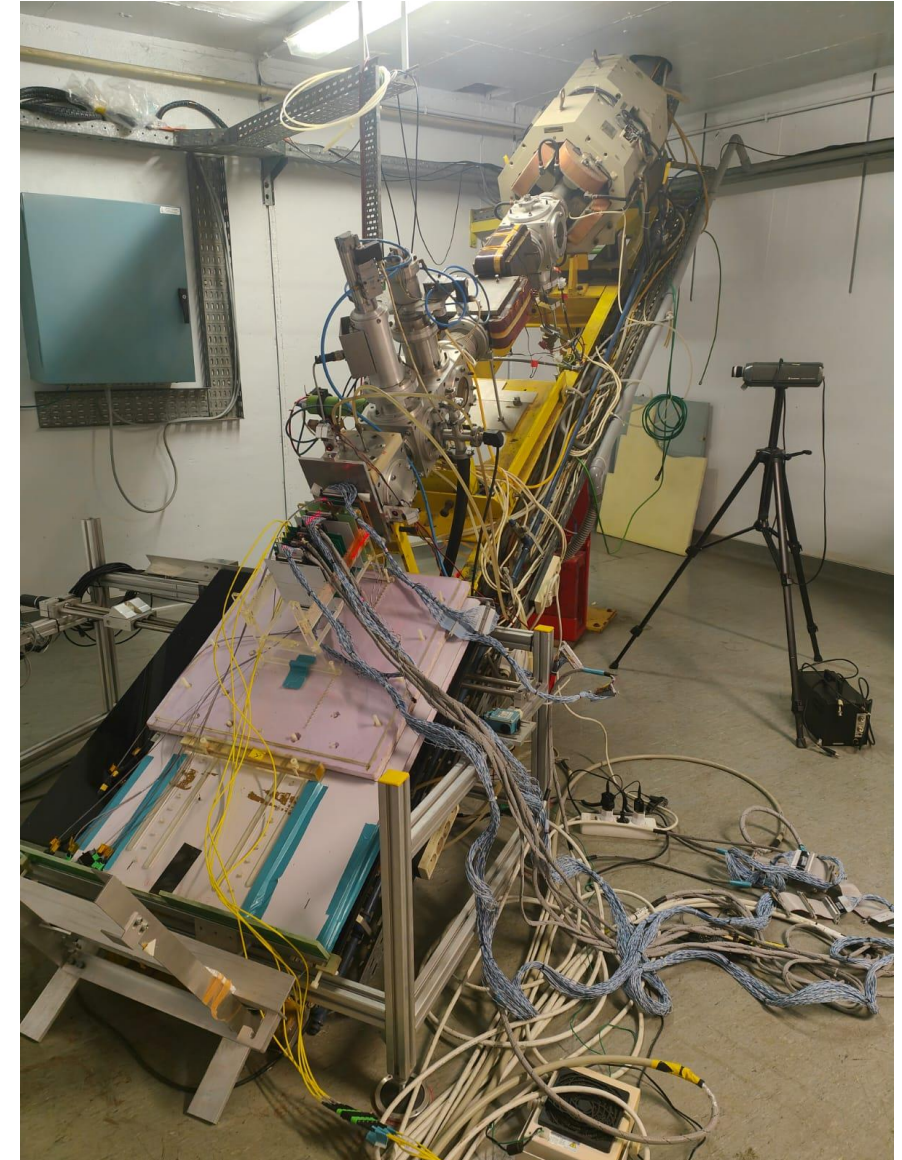
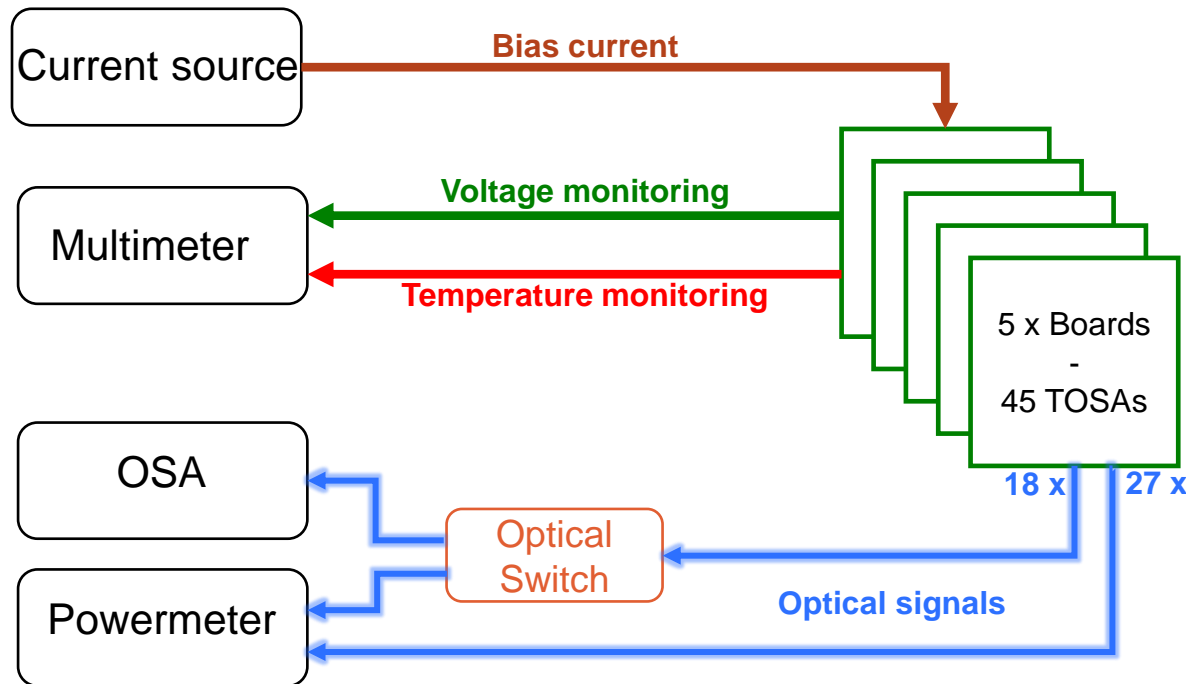
$$-7\text{nm} < \Delta\lambda_{TOSA}(F,T) < +7\text{nm}$$

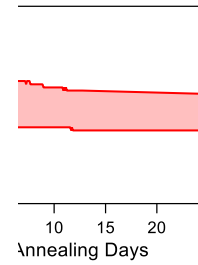
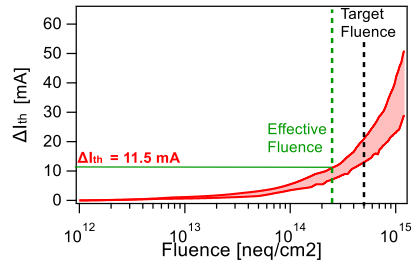
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# TOSA Neutron irradiation test

45 Single-mode TOSAs exposed to neutron beam at UC Louvain Cyclotron facility.

- Total irradiation fluence above  $5 \times 10^{14}$  n/cm<sup>2</sup> 23 MeV Neutrons.
- The samples irradiated were evenly distributed across the four wafers/wavelengths.
- Results from all wafers are grouped due to similar behavior.

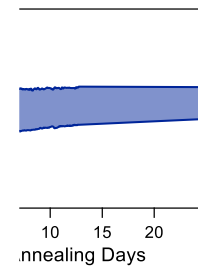
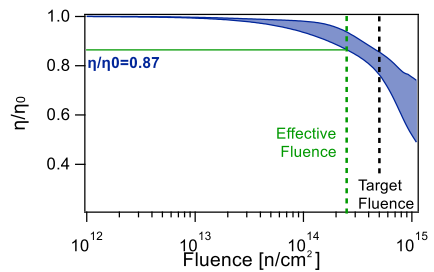




- Radiation damage evaluated at half of the target fluence, namely effective fluence, to take into account recovery due to annealing.

$$\Delta I_{th}(F = 10^{12}) = 0$$

$$\Delta I_{th}(F = 5 \times 10^{14}) = 21 \text{ mA} \quad \Rightarrow \quad \Delta I_{th,eff}(F = 2.5 \times 10^{14}) \approx 11.5 \text{ mA}$$

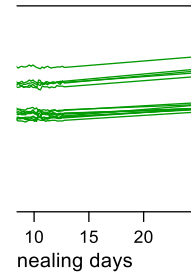
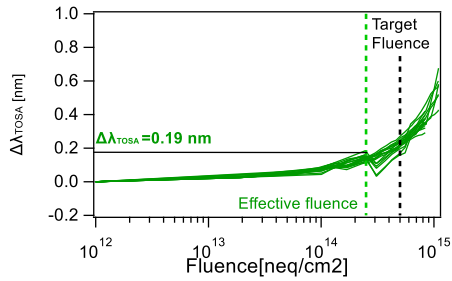


$$\eta/\eta_0(F = 10^{12}) = 0$$

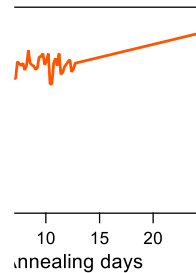
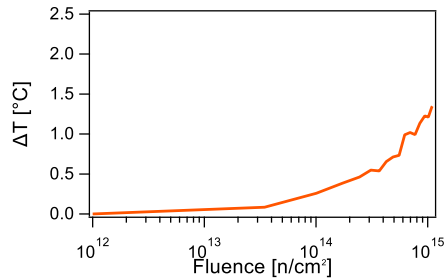
$$\eta/\eta_0(F = 5 \times 10^{14}) = 0.77 \quad \Rightarrow \quad \eta/\eta_0(F = 2.5 \times 10^{14}) = 0.87$$

$$TX_{Penalties}(F = 10^{12}) = 0$$

$$TX_{Penalties}(F = 2.5 \times 10^{14}) = - 0.6 \text{ dB}$$



- Wavelength shift negligible at the effective fluence.



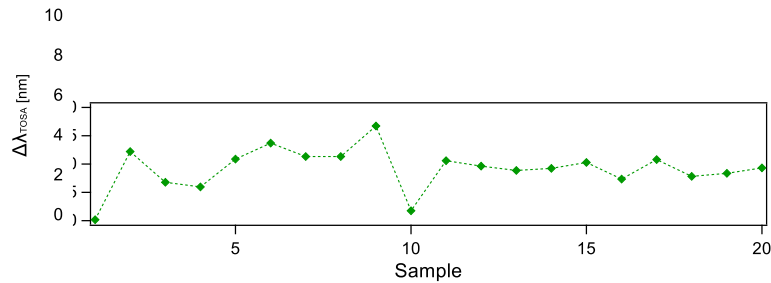
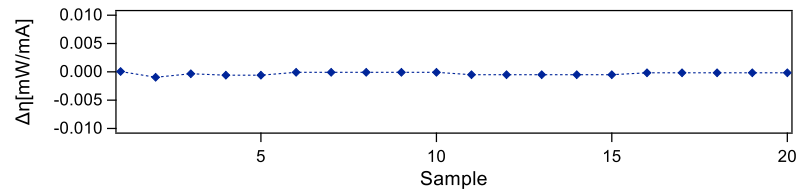
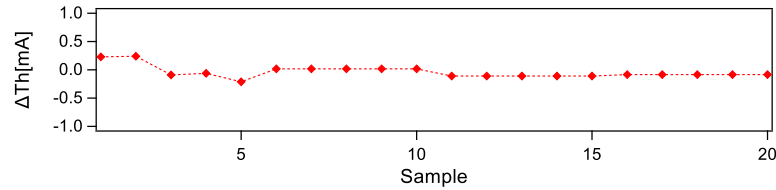
- The wavelength shift is most likely due to a temperature rise in the irradiation room.

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# TOSA Radiation Effects – Gamma Irradiation



20 Samples, 5 per wafer/wavelength, were exposed to Gamma Rays up to 10 kGy to evaluate ionizing dose tolerance. The results show the difference of characteristics before and after irradiation for each sample.

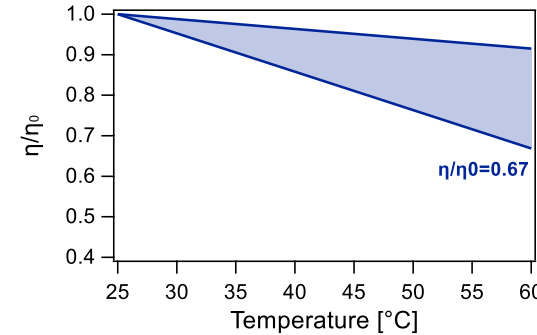
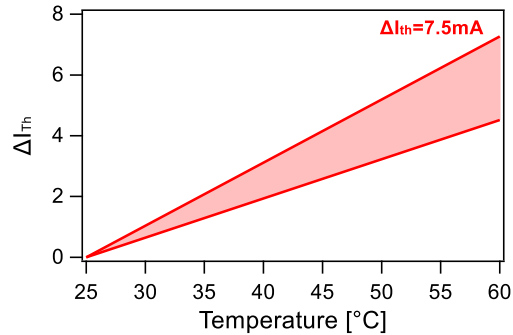


- Threshold current and slope efficiency remains unaffected.
- Negligible variations can be due to temperature variations between pre and post irradiation measurements.

$$\Delta\lambda_{\text{Max}}(10 \text{ kGy}) = 1.7 \text{ nm}$$

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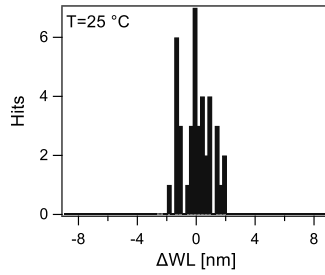
40 Samples, 10 per wafer/wavelength, were characterized in the temperature range [ -5 - +60 ] °C.  
Since TOSA's optoelectronic characteristics degrade at rising temperature, the results are shown only for the range [ 25 - 60 ] °C



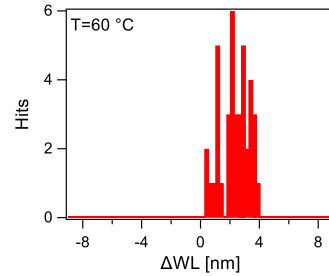
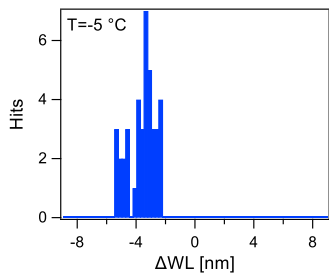
$$\Delta I_{th}(T=60) = 7.5 \text{ mA}$$

$$\eta/\eta_0(T=60) = 0.67$$

$$\Rightarrow \text{Tx}_{\text{Penalties}}(T=60) = -1.74 \text{ dB}$$



- The lasing wavelength of each TOSA differs from the nominal one and stays within manufacturer specifications.



$$\Delta\lambda_{\text{Max}_P}(T=60) = 4 \text{ nm}$$

$$\Delta\lambda_{\text{Max}_N}(T=-5) = -5.5 \text{ nm}$$

$$-7\text{nm} < \Delta\lambda_{\text{TOSA}}(\text{F},\text{T}) < +7\text{nm}$$

$$\Delta\lambda_{\text{Max}_P}(10\text{ kGy}, T=60) = 5.7\text{ nm}$$

$$\Delta\lambda_{\text{Max}_N}(T=5) = -5.5\text{ nm}$$

$$\text{Tx Penalties}_{(\text{CWDM } 2 \times 1)}(\text{F},\text{T}) < 4.2\text{ dB}$$

$$\eta/\eta_0(F = 2.5 \times 10^{14}, T=60) = 0.54 \quad \Rightarrow \quad \text{Tx Penalties}_{(\text{CWDM } 2 \times 1)}(\text{F},\text{T}) = 2.7\text{ dB}$$

$$\text{Tx Penalties}_{(\text{CWDM } 4 \times 1)}(\text{F},\text{T}) < 1.6\text{ dB}$$

$$\eta/\eta_0(F = 10^{12}, T=60) = 0.67 \quad \Rightarrow \quad \text{Tx Penalties}_{(\text{CWDM } 4 \times 1)}(\text{F},\text{T}) = 1.74\text{ dB}$$

Various solutions are being investigated to ensure the link operation:

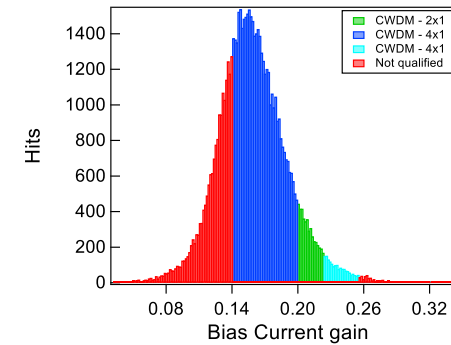
- Increase Rx Sensitivity of the back-end modules.
- Control and reduce the operating temperature of the front-end modules.
- Binning of TOSA by the slope efficiency during production.

What about the threshold current increase?

The laser drivers intended for the full production were categorized upon the bias current provided to guarantee the efficiency of the optical link for conditions within specifications.

The laser driver provide a bias current via 8-bit DAC controlled by the register *Bcreg*

$$I_{\text{bias}} = 2 + \underbrace{0.16}_{\text{Bias current gain}} \times \text{BCreg}\langle 7:0 \rangle \text{ mA}$$



The current gain for different chips spreads around the nominal value. This spread is exploited to compensate for the different threshold current increase in the two designs.

$$\Delta I_{\text{th (CWDM 4x1)}} (F = 10^{12}, T=60) = 7.5 \text{ mA}$$

$$\Delta I_{\text{th (CWDM 2x1)}} (F = 2.5 \times 10^{14}, T=60) = 19 \text{ mA}$$

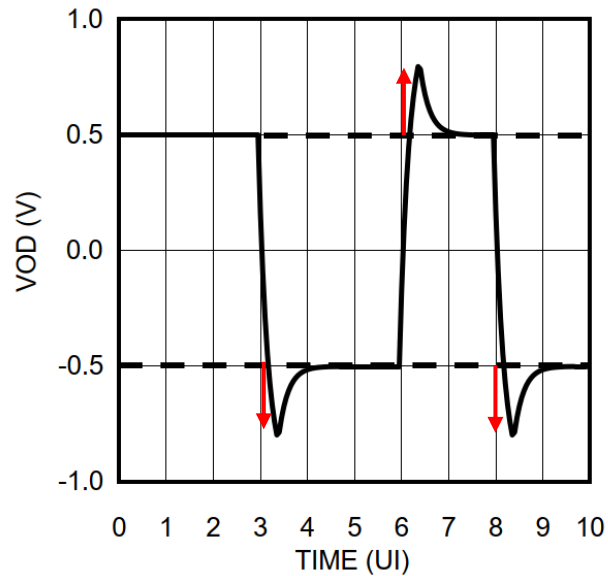
- The CWDM-Link project is approaching the production phase and the qualification of the TOSAs selected was required.
- The TOSAs were exposed to Neutron and Gamma irradiations coherently with the specifications.
- TOSA's characteristics were also evaluated within the operating temperature range specified.
- The TOSAs qualified to be used in both links of the project, with more attention to be dedicated on the power budget of the CWDM 4x1.
- The laser drivers intended for the CWDM-Link production were categorized to compensate for the threshold current increase foreseen.



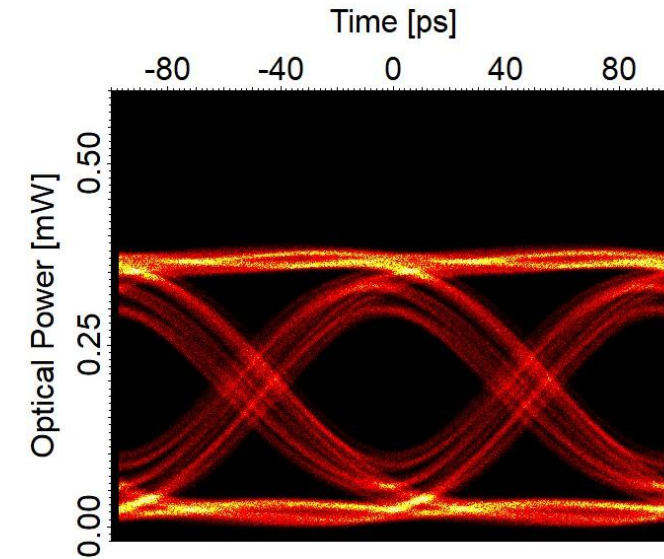
Thanks for the attention!

## Pre-emphasis concept

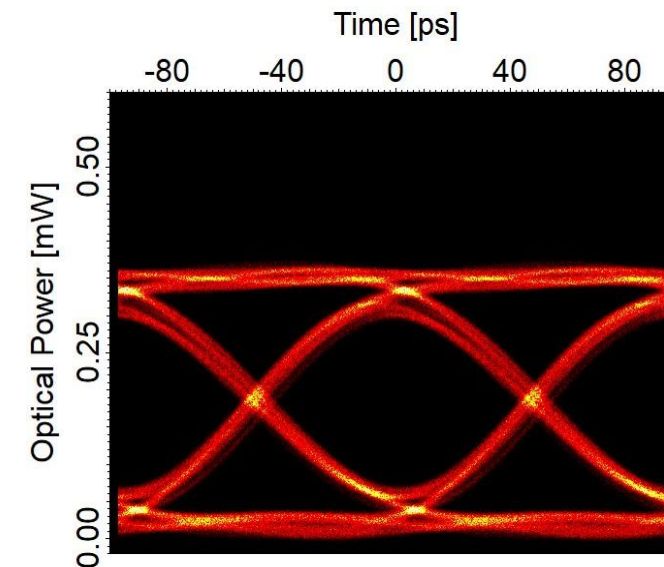
Reduces **jitter** and **signal degradation** induced by the channel during propagation



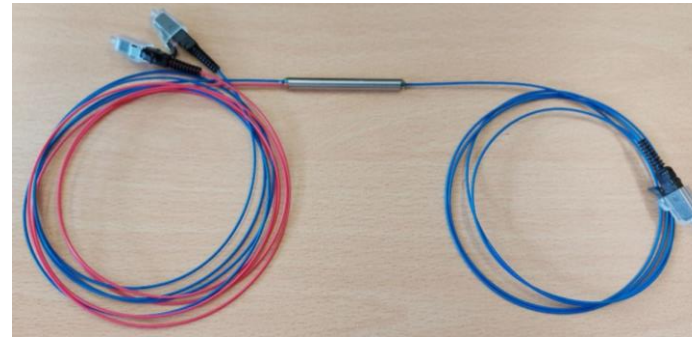
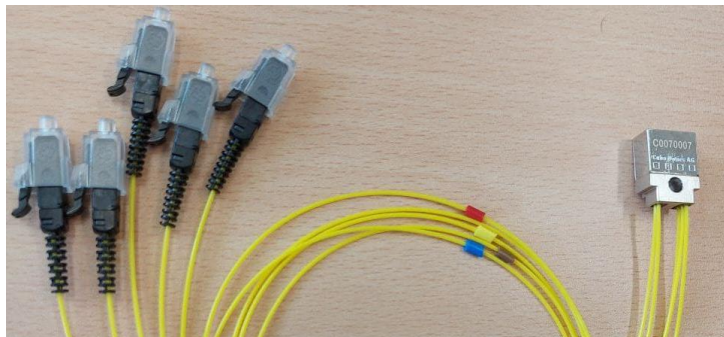
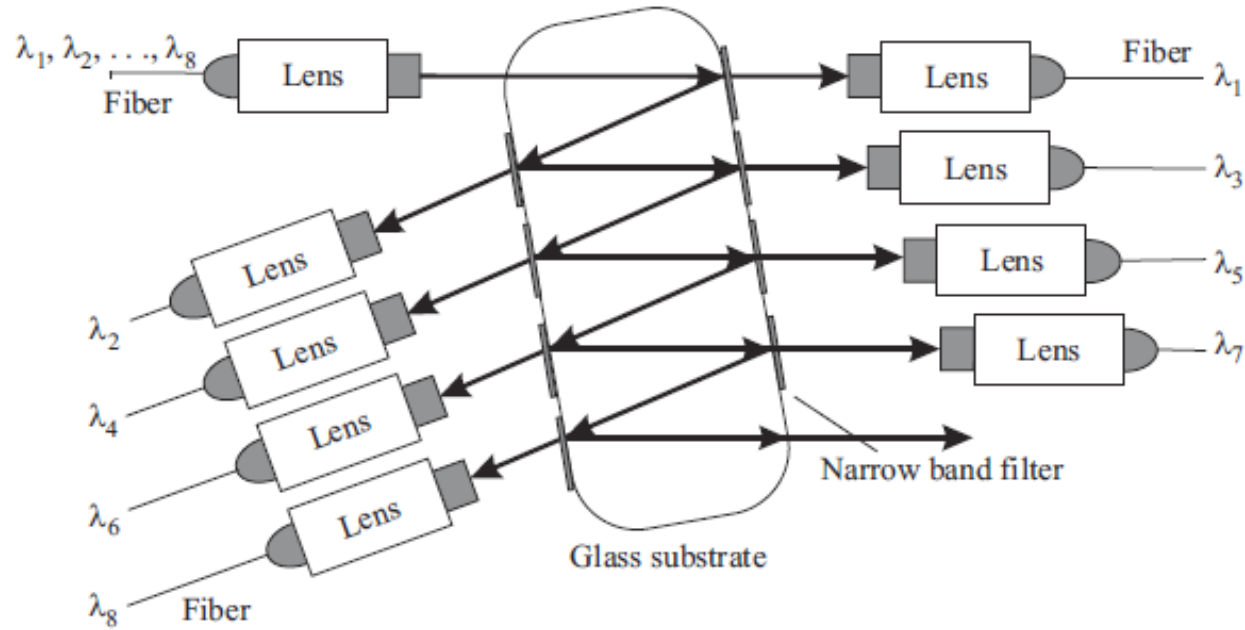
## Without pre-emphasis

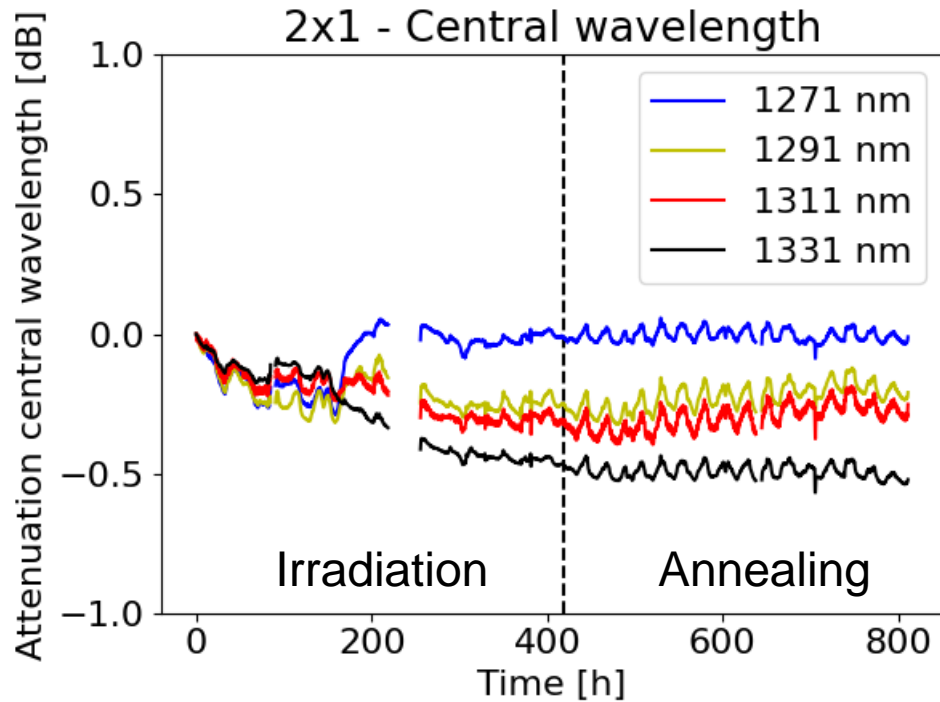


## With pre-emphasis (7.2 dB)

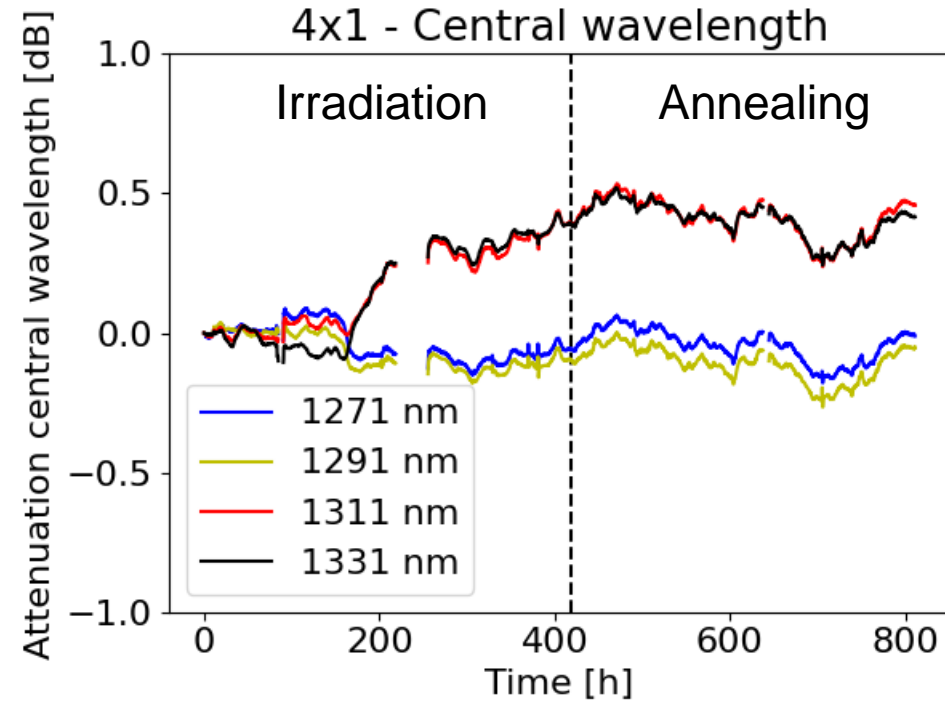


## Thin-Film Filter technology





The room was open after ~150h to change some other device. This caused a significant temperature change.



No significant loss due to darkening of optical components was observed

# TOSA Temperature effects

