Eye safety analysis for 802.3cz links

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Introduction & objectives

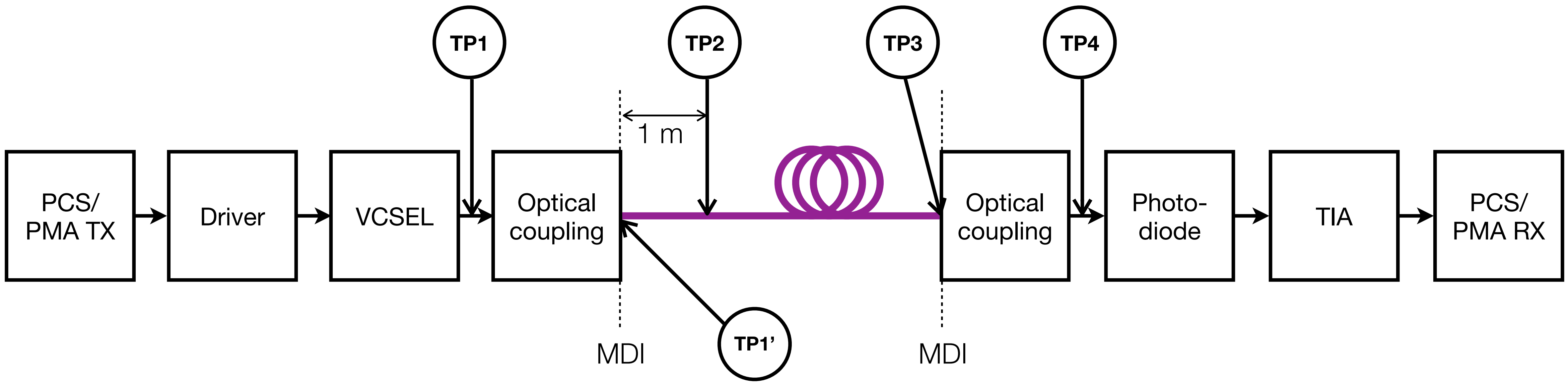
- Eye safety is key for automotive applications
  - Even if these connections are "under the hood", it could be easy for any non-trained car user to unplug a connection and be exposed to the laser radiation
  - To avoid any labelling and additional precautions, either the Laser Class 1 or Laser Class 1M should be achieved
  - Laser Class 1 is defined as safe under reasonably foreseeable conditions of operation including the use of optical instruments for intra-beam viewing. This means that the maximum level of radiation must be less or equal to the accessible emission limits for Class 1. (IEC 60825-1 Safety of Laser Products Part 1 and IEC 60825-2 Safety of Laser Products Part 2)
  - Laser Class 1M is as Class 1 without including optical instruments for intra-beam viewing
- Eye safety requirement
  - In other automotive optical communications networks, i.e. MOST and GEPOF, Laser Class 1 is a requirement
  - 802.3cz PMD should have meeting Laser Class 1 as an objective
- VCSEL average power depends of temperature and current:
  - In high temperature, where low current should be applied (making possible high reliability), the quantum efficiency is lower
  - In low temperature, where high current needs to be applied to compensate distortion and reliability is not critical, the quantum efficiency is higher
  - Big injected power differences due to wide operation ranges in temperature and current

Introduction & objectives

- Next slides will show how the VCSEL AOP varies with temperature considering all the 850 nm devices characterized
    - Quantum efficiency is expected equal or even higher in longer wavelength VCSELs (i.e. 980nm), therefore higher or equal powers
- Analysis of AOP limits for achieving Laser Class 1 and Laser Class 1M at wavelengths of 850 nm and 980 nm for EBO (Expanded Beam Optics) and BC (Butt Coupling) optical coupling techniques will be provided
- General method to meet eye safety will be proposed based on state diagrams operating in the PHY

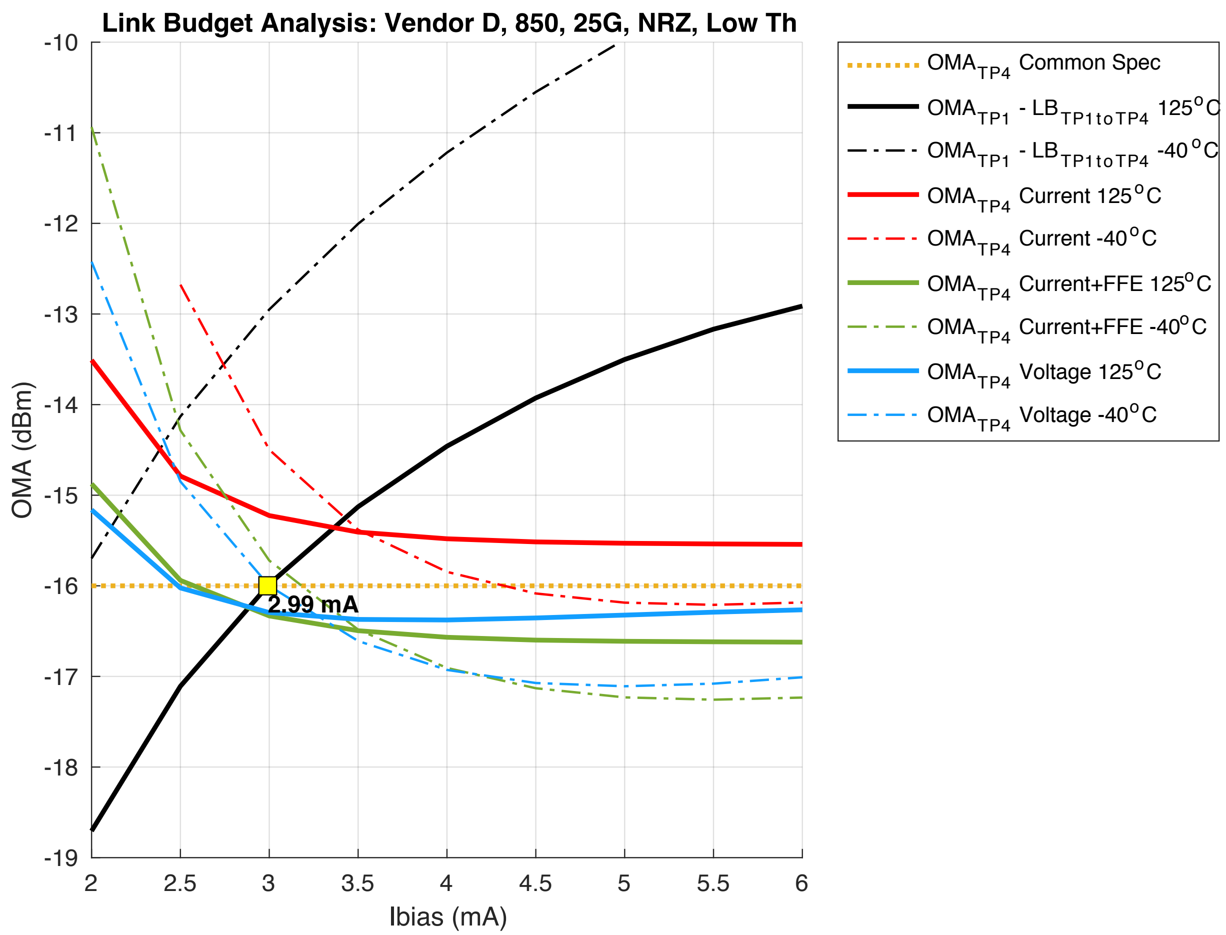
AOP measurements

Link model — test points definition



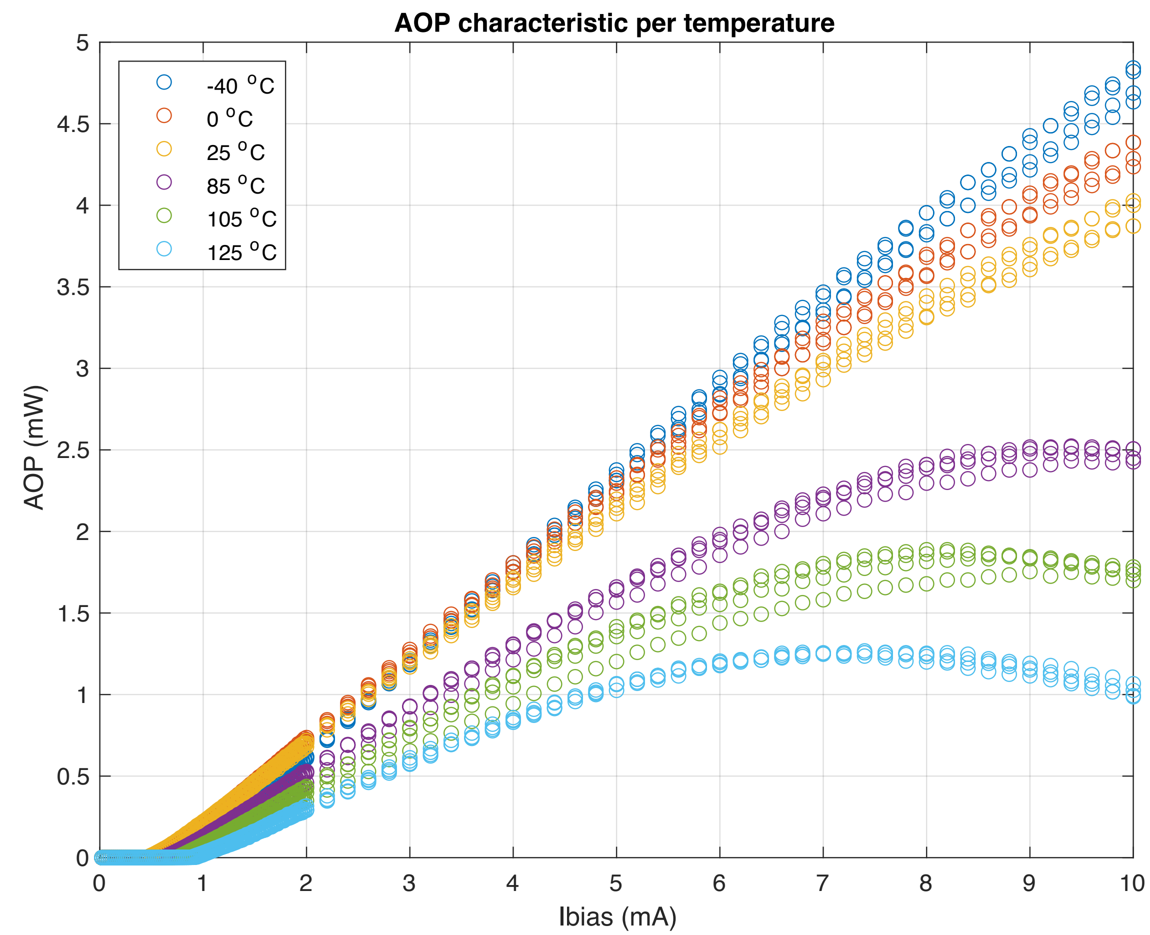
- Test points defined in **perezaranda_3cz_01_131020_link_model.pdf**, and used here again for consistency
  - Note: definition of TP1 and TP4 is different of usual definition used in 802.3
- **TP1:** VCSEL optical transmit signal (see perezaranda_OMEGA_01b_0720_VCSEL_test_methods)
- **TP1':** Transmitter MDI, defined for eye-safety test and definition purposes
- **TP2:** Optical transmit signal at the output end of 1 meter of optical fiber consistent with the link segment type connected to MDI (Media Dependent Interface)
- **TP3:** Optical receive signal at the output of the fiber optic cabling, which in a link segment is connected to the receiver (i.e. MDI)
- **TP4:** Optical receive signal coupled into the photodiode device

Vendor D, 850 nm, 25G, NRZ, low threshold



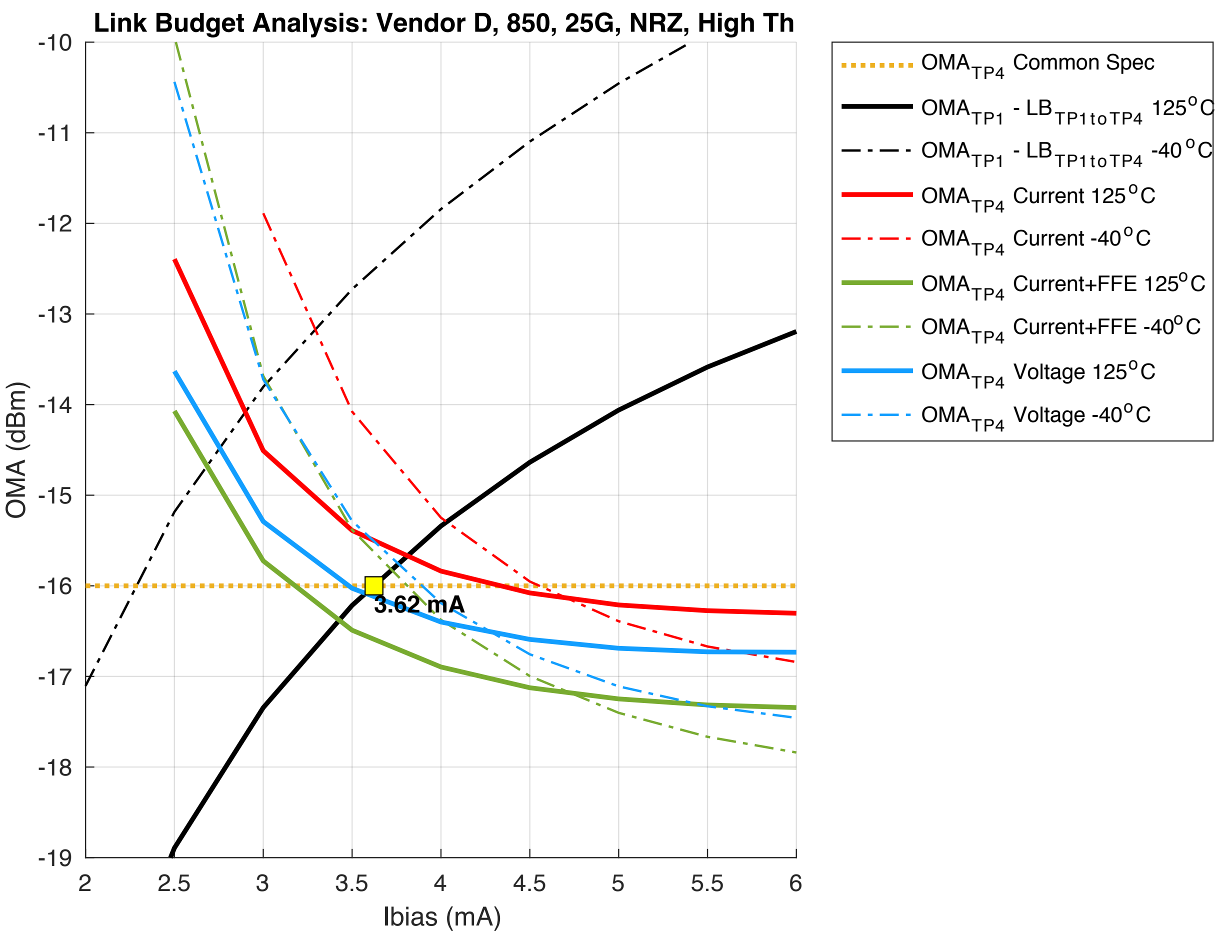
perezaranda_3cz_01_271020_25G_link_budget

TP1



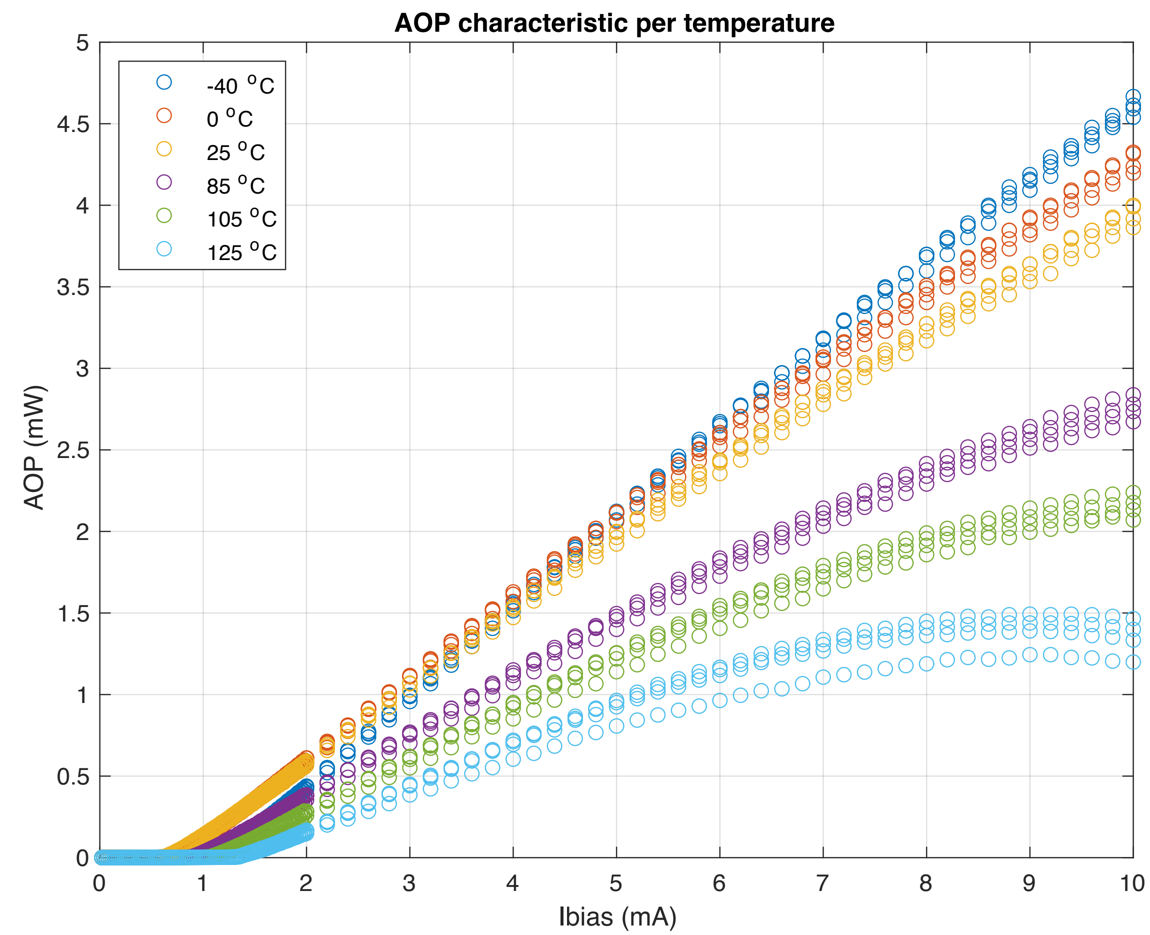
perezaranda_OMEGA_05a_0720_VendorD_VCSEL

Vendor D, 850 nm, 25G, NRZ, high threshold



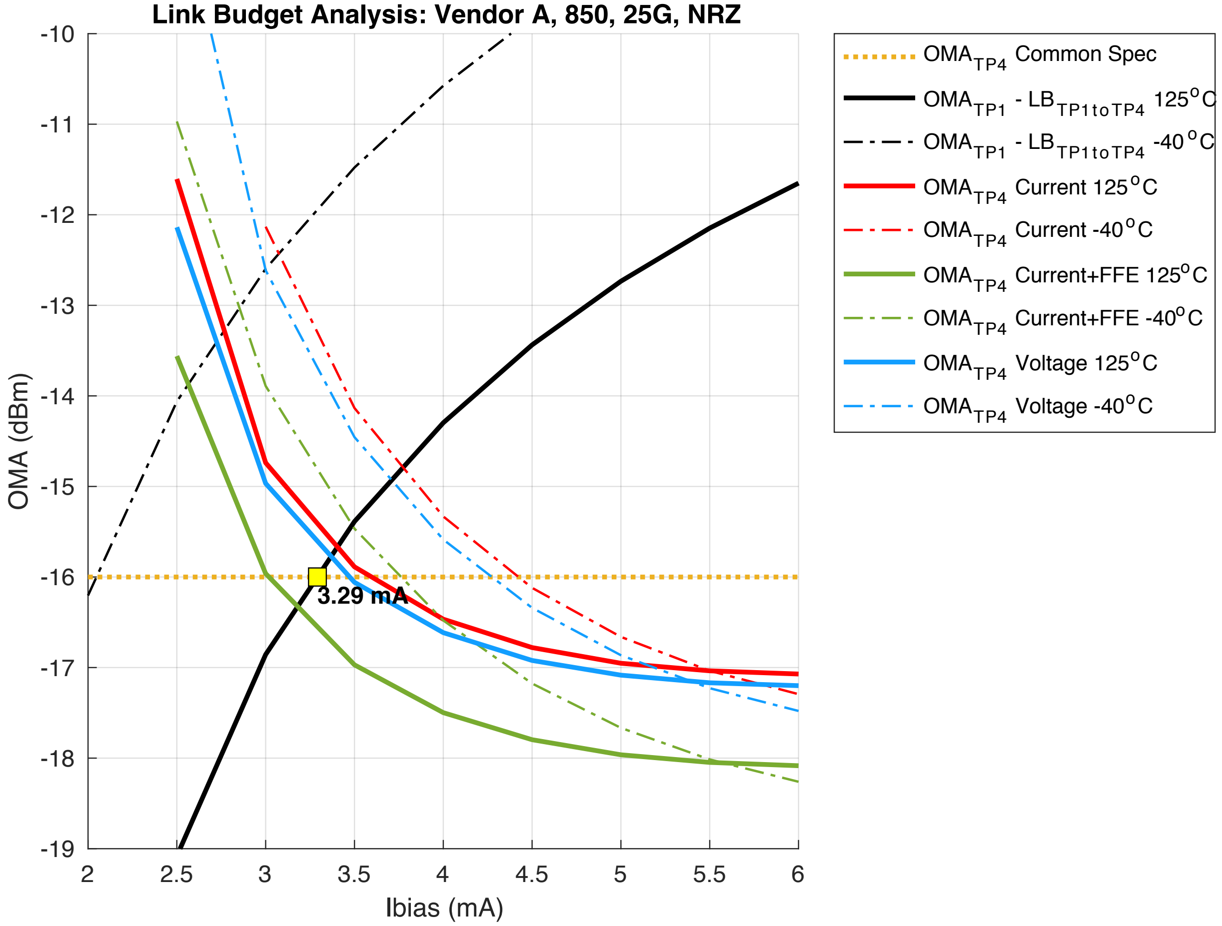
perezaranda_3cz_01_271020_25G_link_budget

TP1



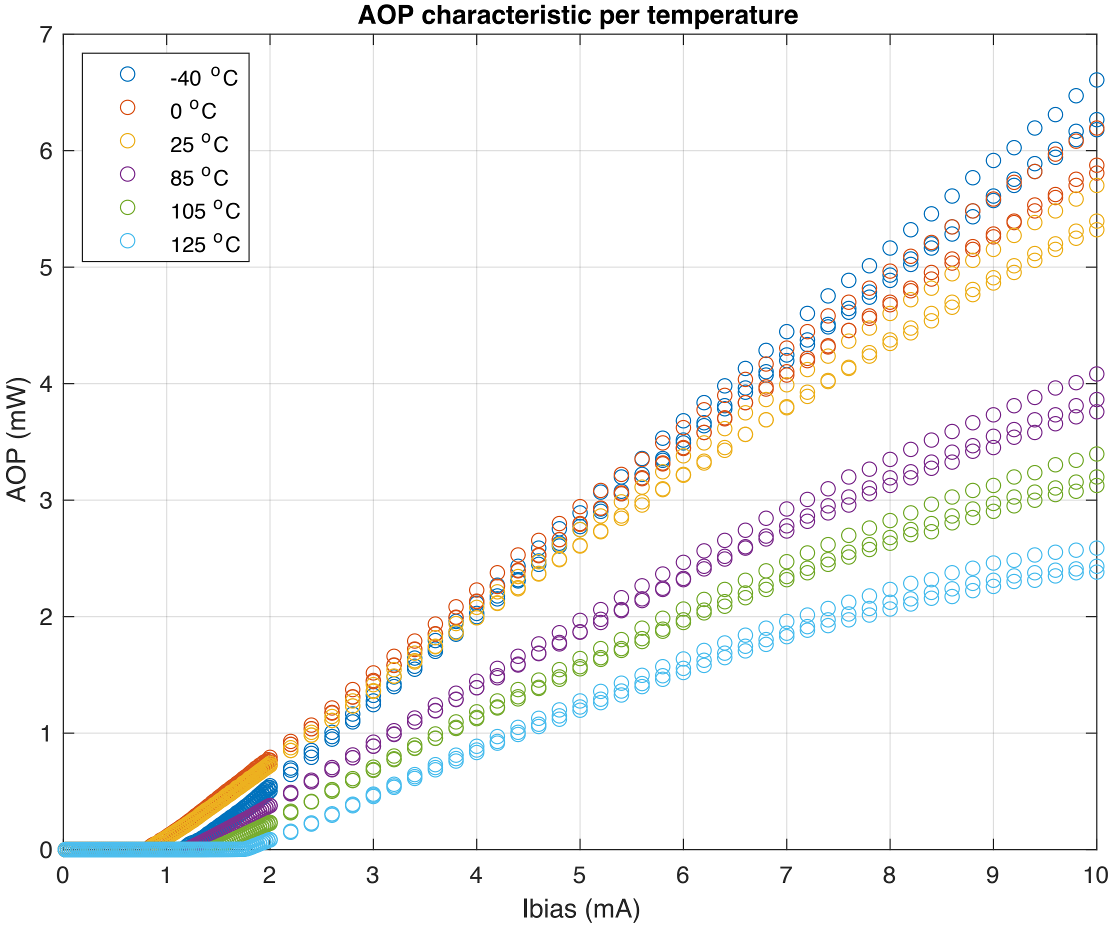
perezaranda_OMEGA_05a_0720_VendorD_VCSEL

Vendor A, 850 nm, 25G, NRZ



perezaranda_3cz_01_271020_25G_link_budget

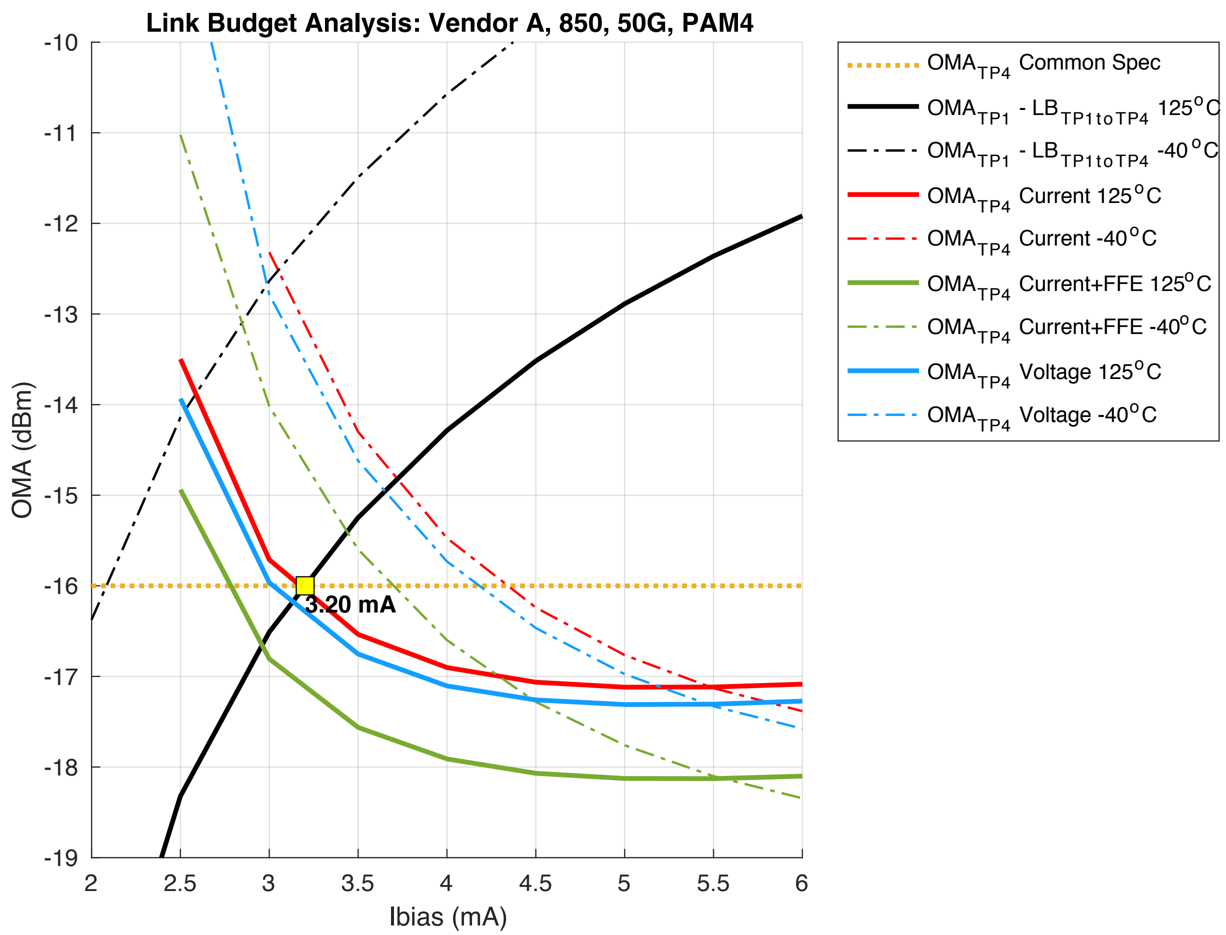
TP1



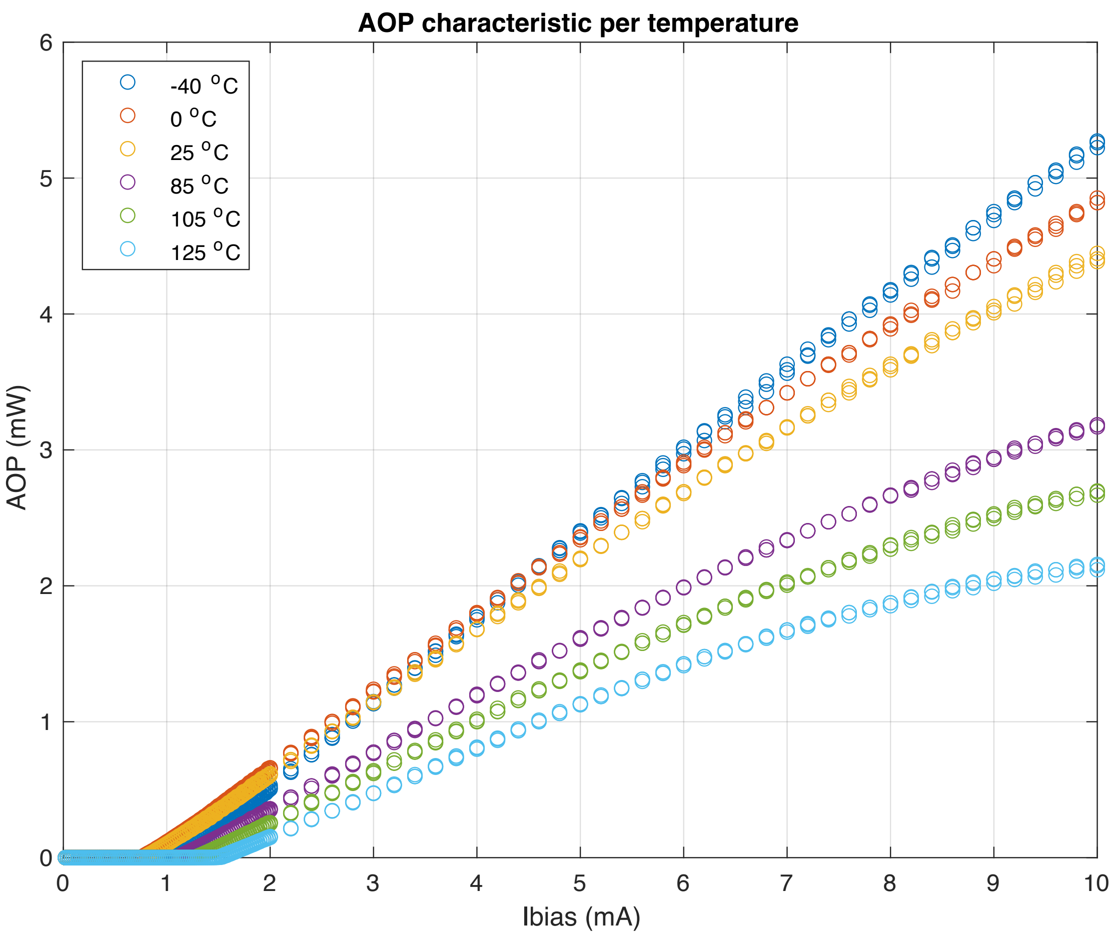
perezaranda_OMEGA_02a_0720_VendorA_VCSEL

Vendor A, 850 nm, 50G, PAM4

TP1



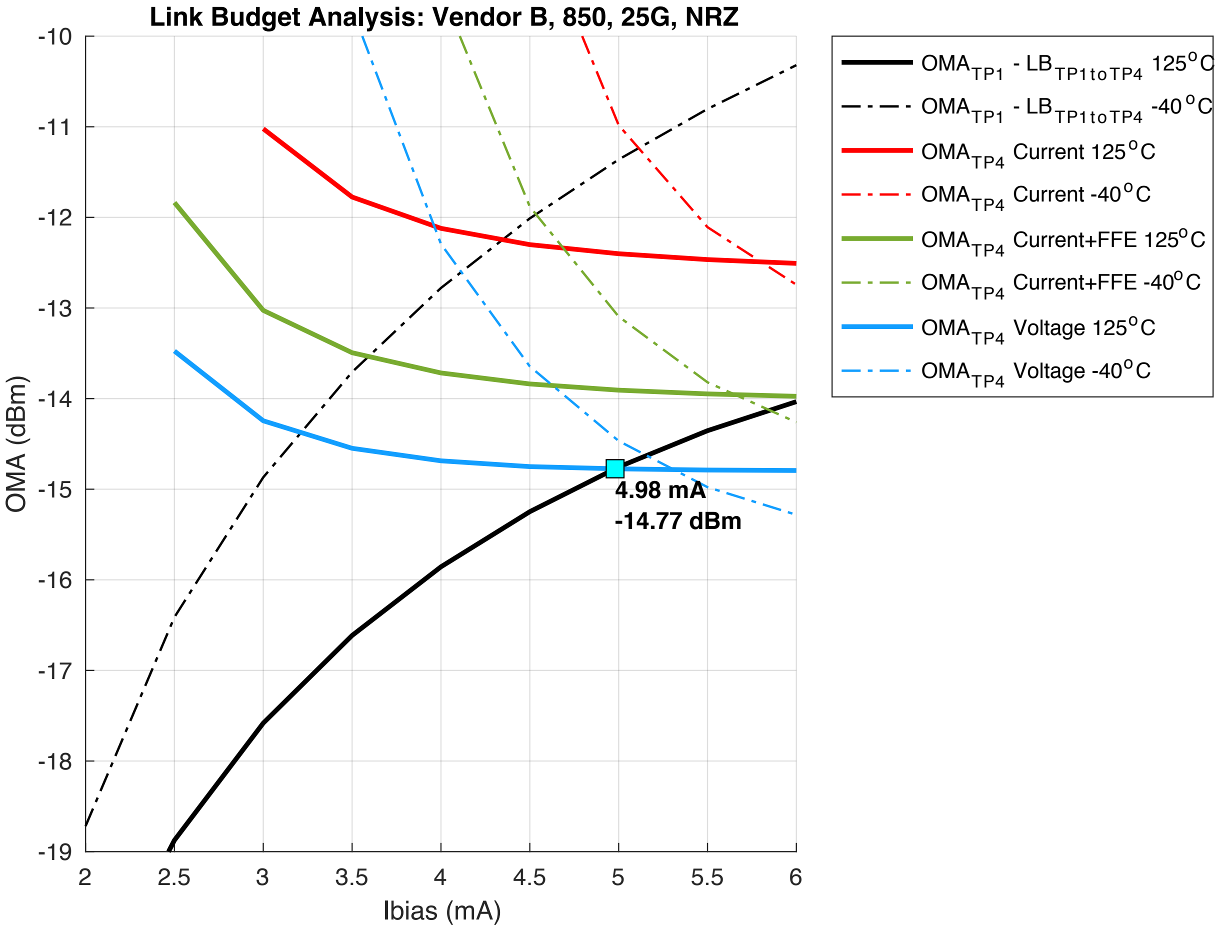
perezaranda_3cz_01_271020_25G_link_budget

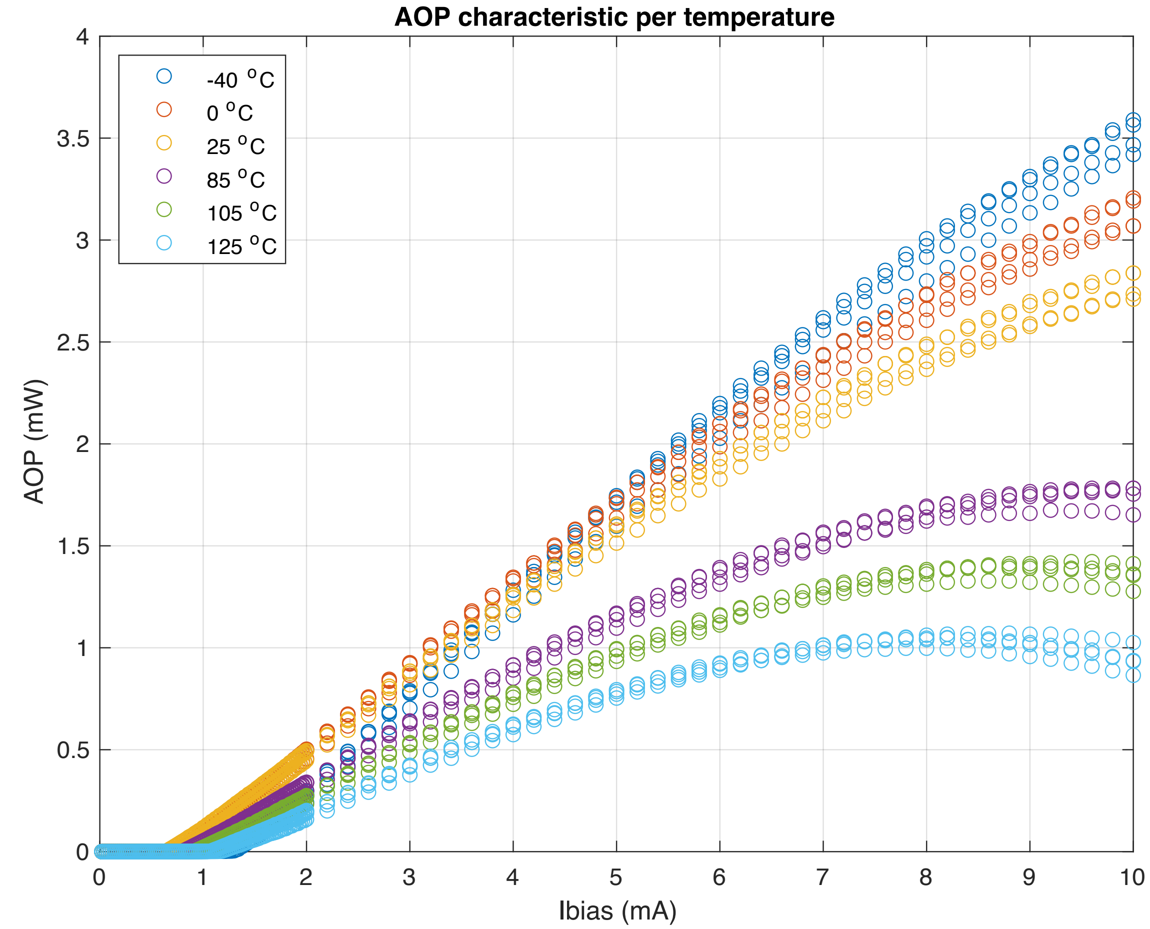


perezaranda_OMEGA_02a_0720_VendorA_VCSEL

Vendor B, 850 nm, 25G, NRZ

TP1



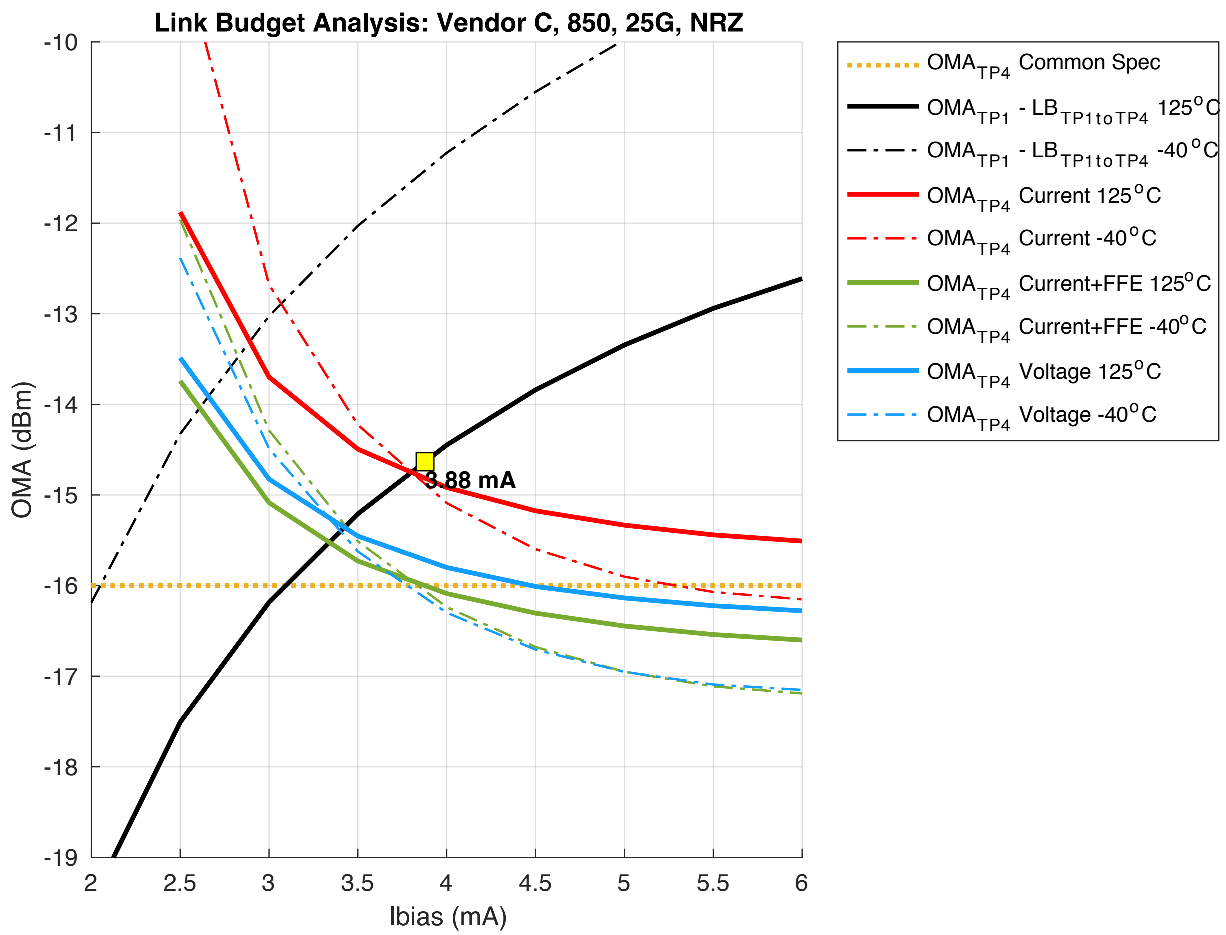


perezaranda_3cz_01_271020_25G_link_budget

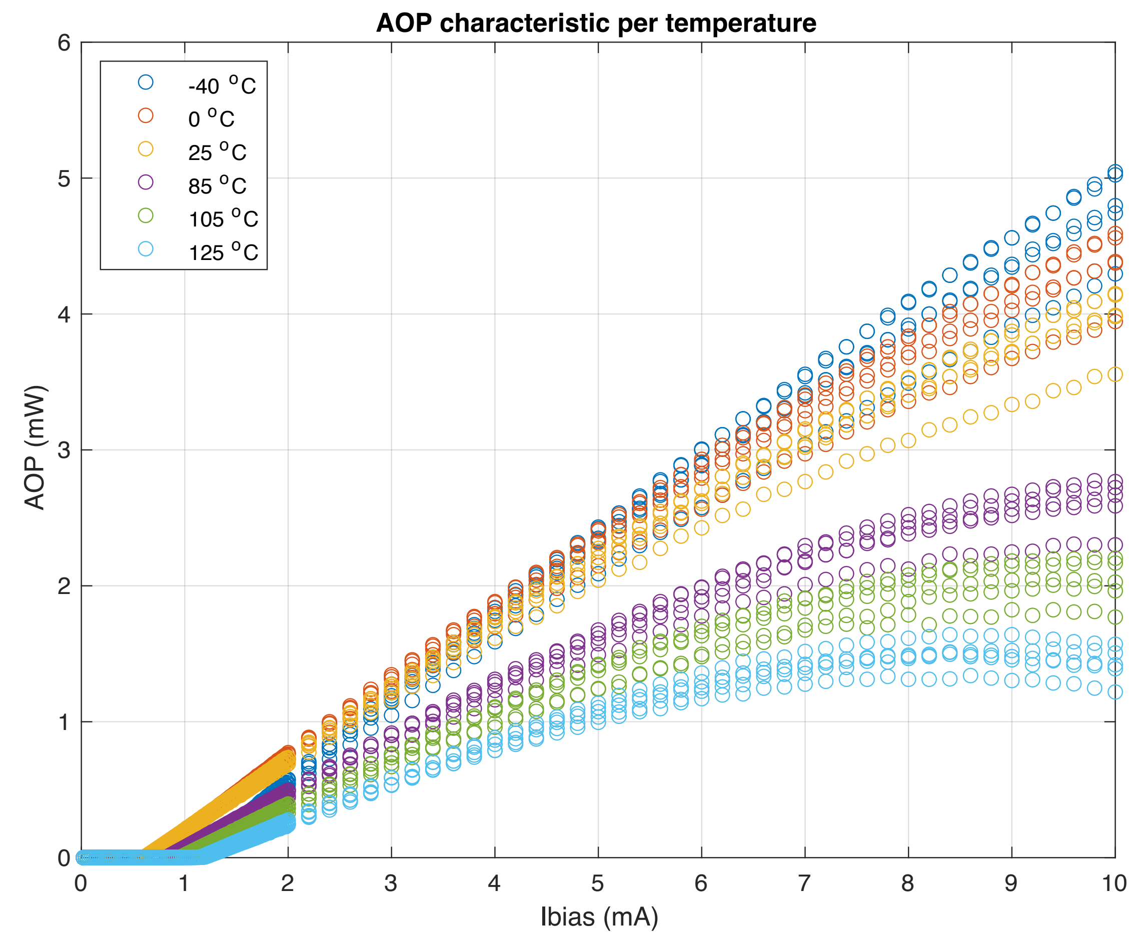
perezaranda_OMEGA_03a_0720_VendorB_VCSEL

Vendor C, 850 nm, 25G, NRZ

TP1

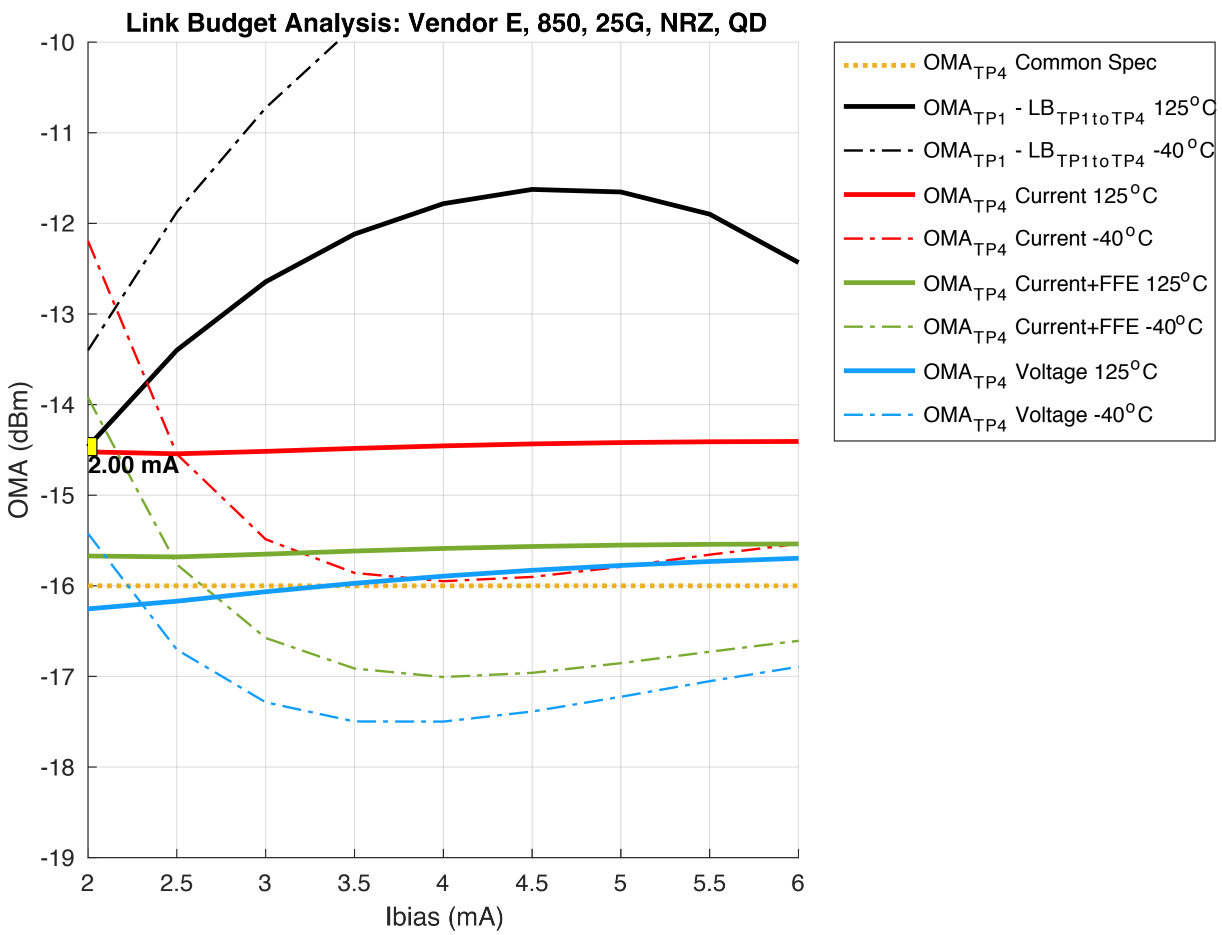


perezaranda_3cz_01_271020_25G_link_budget



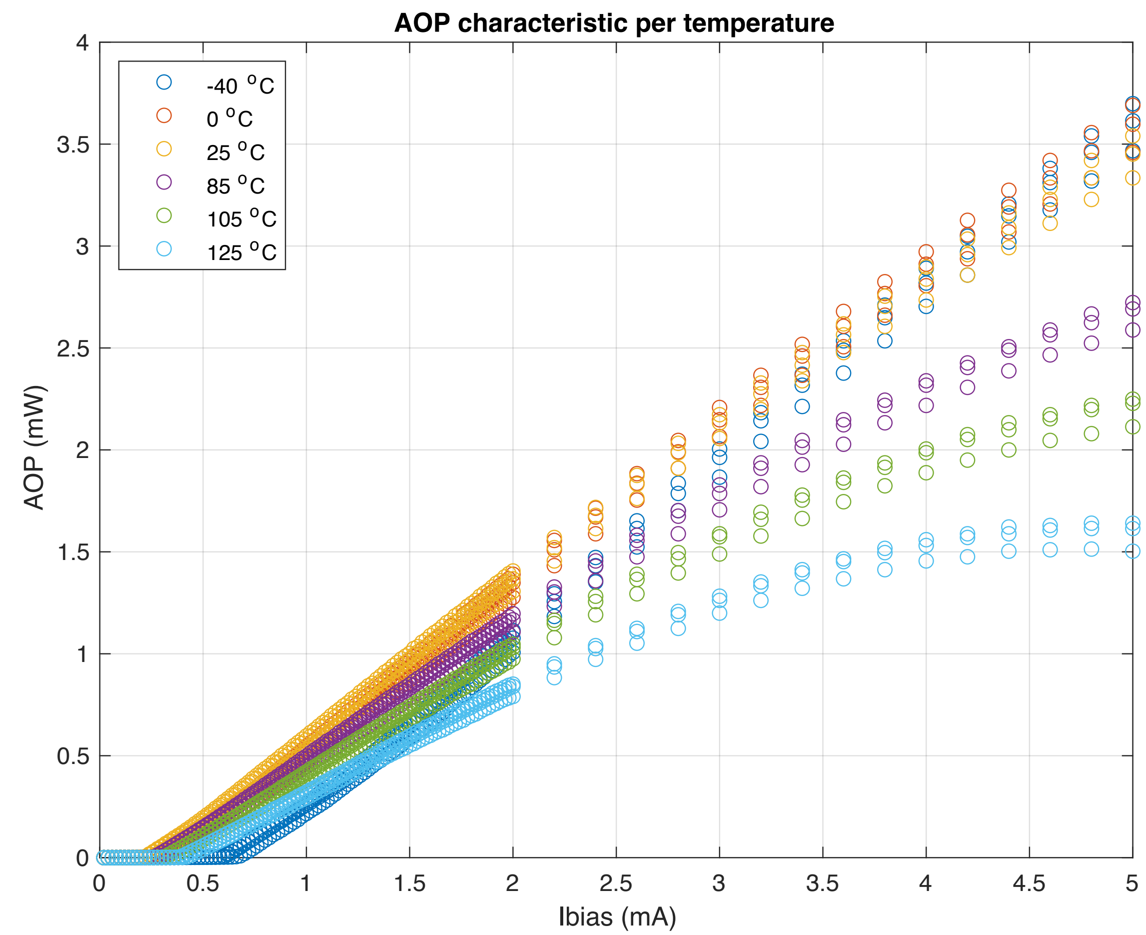
perezaranda_OMEGA_04a_0720_VendorC_VCSEL

Vendor E, 850 nm, 25G, NRZ, QD



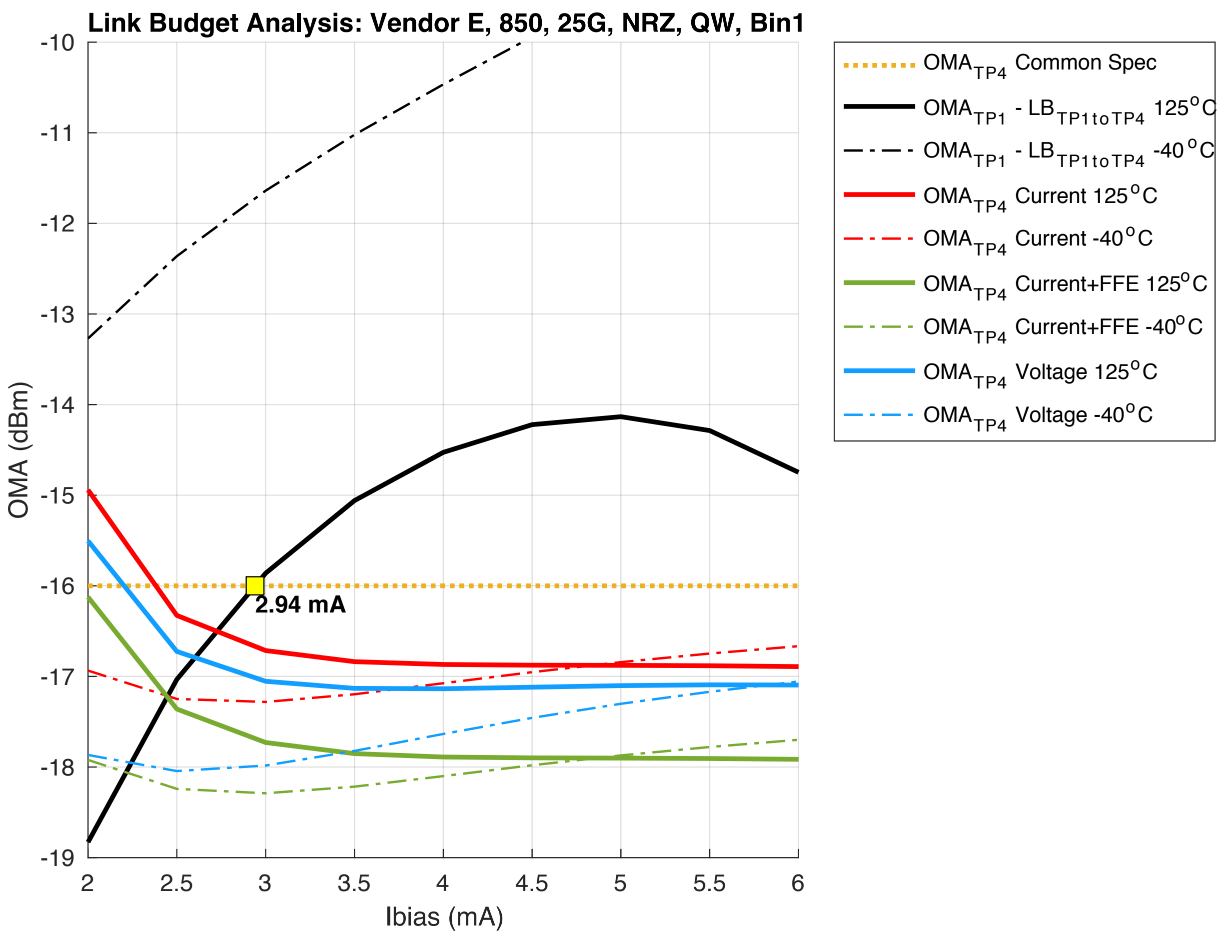
perezaranda_3cz_01_271020_25G_link_budget

TP1



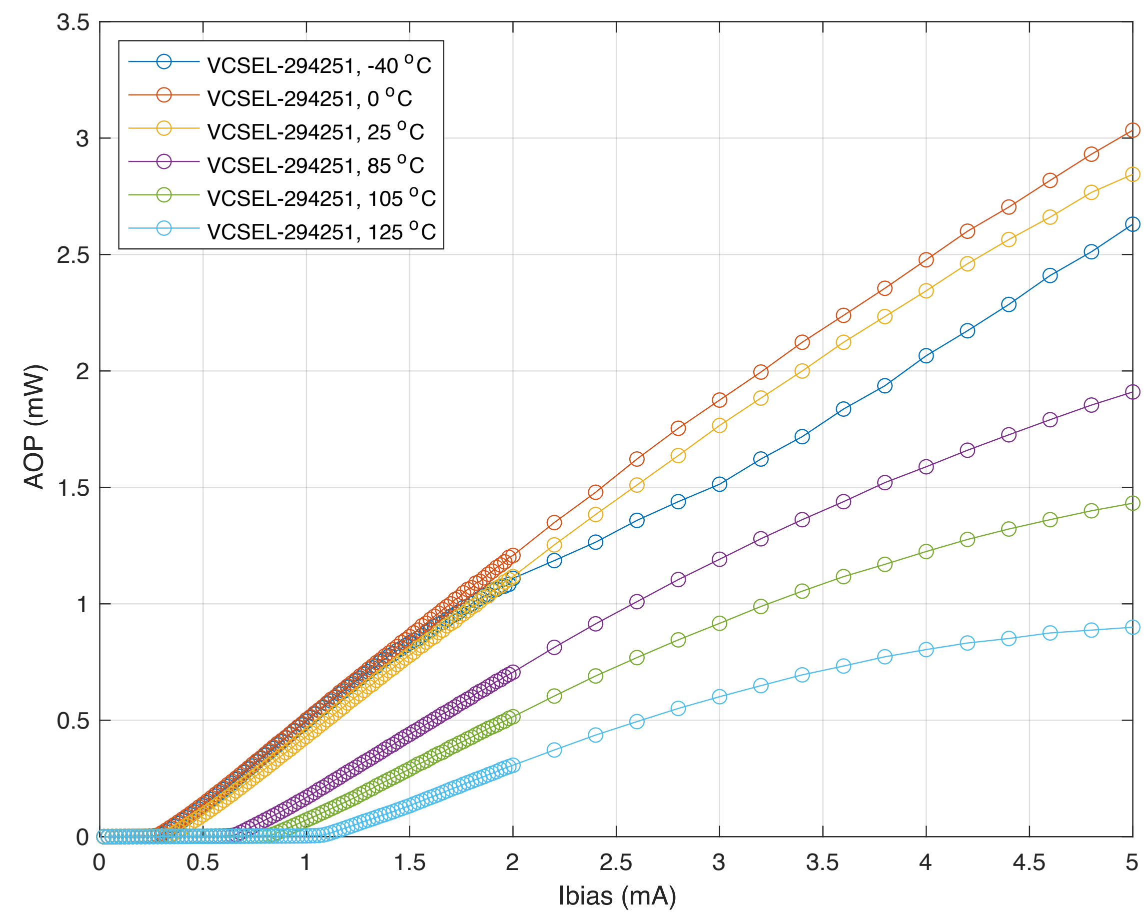
perezaranda_3cz_01b_0820_VendorE_VCSEL

Vendor E, 850 nm, 25G, NRZ, QW, Bin1



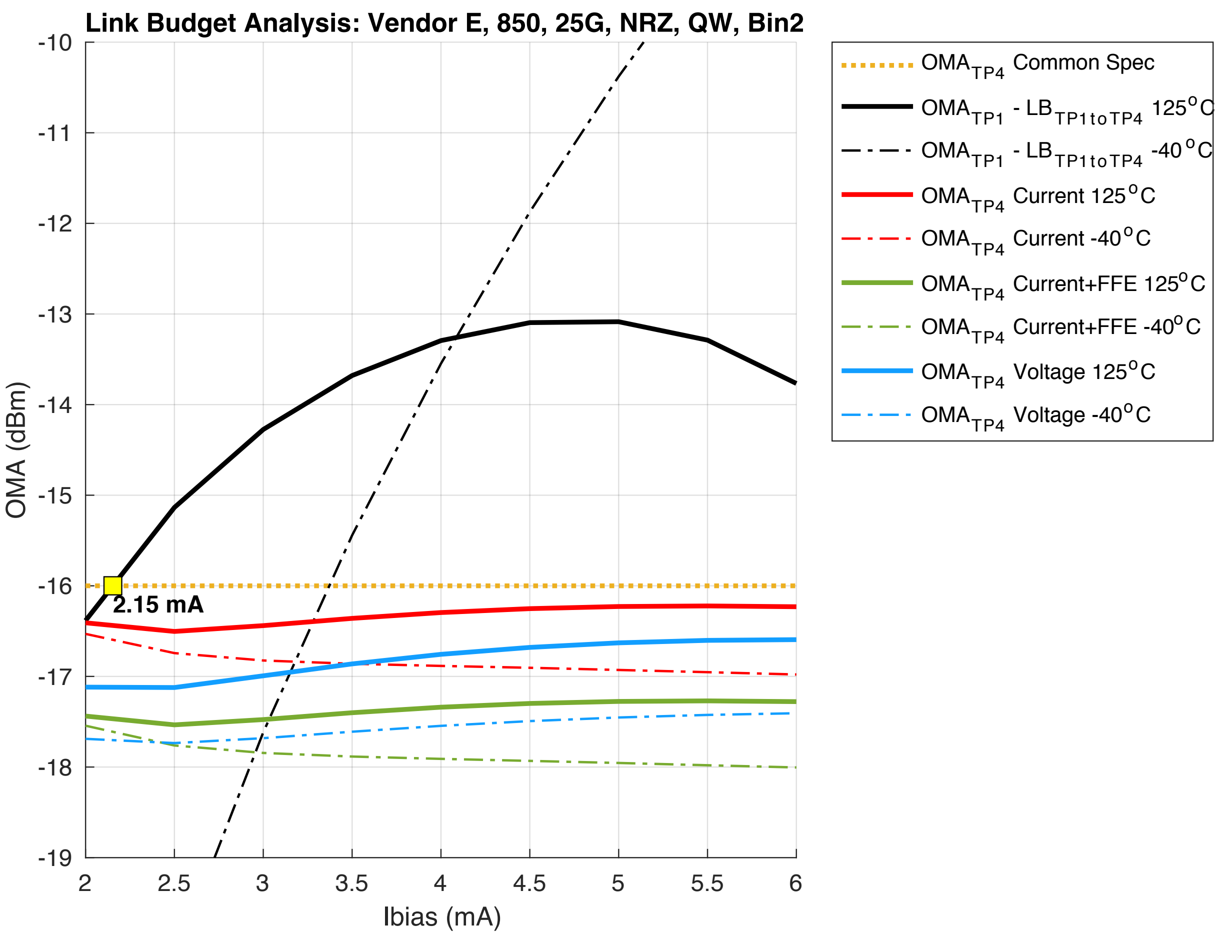
perezaranda_3cz_01_271020_25G_link_budget

TP1



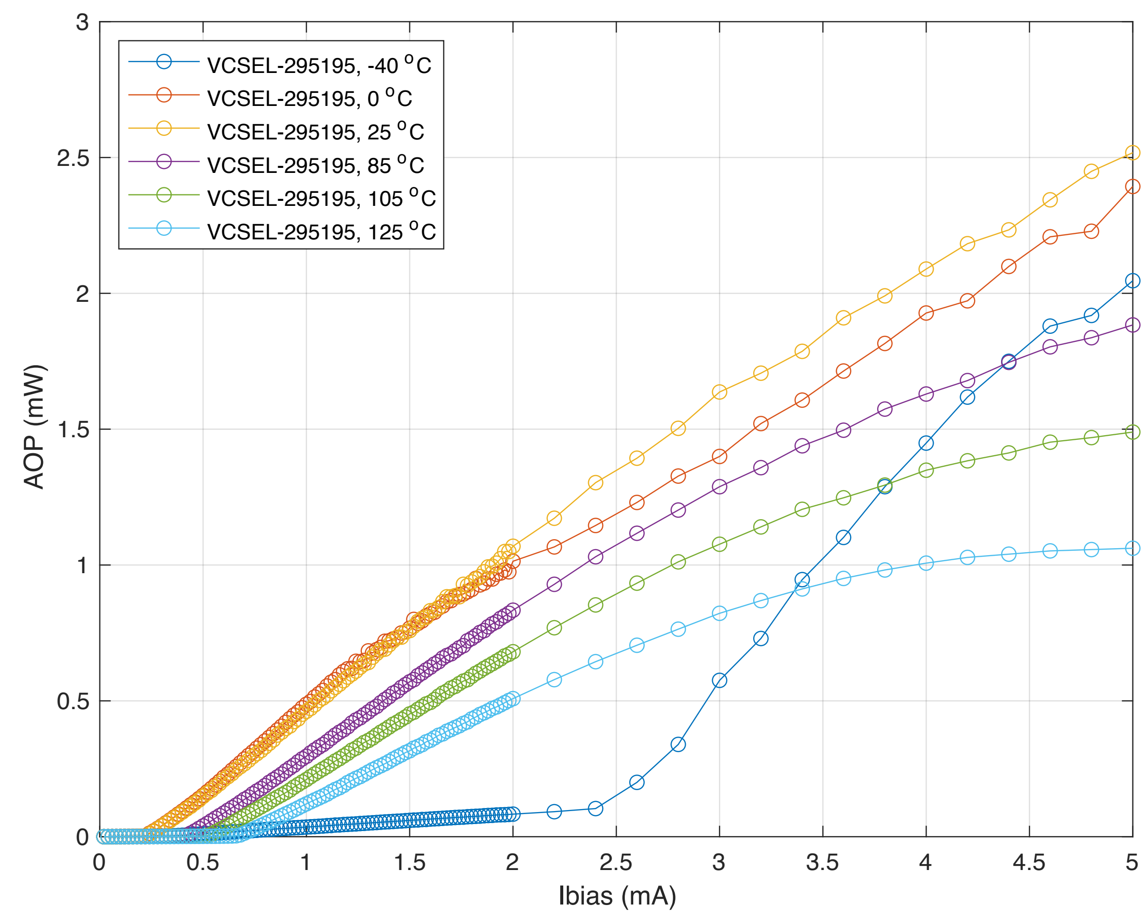
perezaranda_3cz_01b_0820_VendorE_VCSEL

Vendor E, 850 nm, 25G, NRZ, QW, Bin2



perezaranda_3cz_01_271020_25G_link_budget

TP1



perezaranda_3cz_01b_0820_VendorE_VCSEL

AOP results summary

AOP summary

VCSEL model	Cold T_{BS} for max power (ºC)	Ibias (mA)			AOP_{TP1} (mW)			VCSEL SE variation intrabin (dB)
		T_{BS} Cold	T_{BS} = 25ºC	T_{BS} = 125ºC	T_{BS} Cold	T_{BS} = 25ºC	T_{BS} = 125ºC	
Vendor D, 850, 25G, NRZ, Low Th	-40	6.00	5.00	2.99	2.95	2.16	0.61	0.5
Vendor D, 850, 25G, NRZ, High Th	-40	6.00	5.00	3.62	2.67	2.00	0.60	0.5
Vendor A, 850, 25G, NRZ	-40	6.00	5.00	3.29	3.70	2.75	0.59	0.5
Vendor A, 850, 50G, PAM4	-40	6.00	5.00	3.20	3.60	2.73	0.57	0.5
Vendor B, 850, 25G, NRZ	-40	6.00	5.00	4.98	2.20	1.61	0.80	0.5
Vendor C, 850, 25G, NRZ	-40	6.00	5.00	3.88	3.00	2.28	0.85	0.5
Vendor E, 850, 25G, NRZ, QD	-40	5.00	4.00	2.00	3.70	2.90	0.85	0.5
Vendor E, 850, 25G, NRZ, QW, Bin1	0	5.00	4.00	2.94	3.00	2.34	0.60	0.5
Vendor E, 850, 25G, NRZ, QW, Bin2	25	5.00	4.00	2.15	2.40	2.05	0.59	0.5

- Several assumptions need to be considered in the following analysis:
  - A variation of slope efficiency is considered as worst case power in TP1
  - No VCSEL aging is considered
  - T_{BS} = 25ºC is the min temperature for garage operations ($T_{AMB-ECU}$ ~ 5ºC, T_{AMB} lower).

AOP results summary (realistic coupling design considered)

Butt Coupling / Physical Contact

TP1 to TP1' min IL (dB)	TP1' to TP2 min IL (dB)	TP2 to TP3 min IL (dB)	$AOP_{TP1'}$ (dBm)			AOP_{TP2} (dBm)			AOP_{TP3} (dBm), w/c		
			T_{BS} Cold	T_{BS} = 25ºC	T_{BS} = 125ºC	T_{BS} Cold	T_{BS} = 25ºC	T_{BS} = 125ºC	T_{BS} Cold	T_{BS} = 25ºC	T_{BS} = 125ºC
1.37	0.16	0.16	3.83	2.47	-3.02	3.67	2.31	-3.18	3.51	2.15	-3.34
1.37	0.16	0.16	3.40	2.14	-3.09	3.24	1.98	-3.25	3.08	1.82	-3.41
1.37	0.16	0.16	4.81	3.52	-3.16	4.65	3.36	-3.32	4.49	3.20	-3.48
1.37	0.16	0.16	4.69	3.49	-3.31	4.53	3.33	-3.47	4.37	3.17	-3.63
1.37	0.16	0.16	2.55	1.20	-1.84	2.39	1.04	-2.00	2.23	0.88	-2.16
1.37	0.16	0.16	3.90	2.71	-1.58	3.74	2.55	-1.74	3.58	2.39	-1.90
1.37	0.16	0.16	4.81	3.75	-1.58	4.65	3.59	-1.74	4.49	3.43	-1.90
1.37	0.16	0.16	3.90	2.82	-3.09	3.74	2.66	-3.25	3.58	2.50	-3.41
1.37	0.16	0.16	2.93	2.25	-3.16	2.77	2.09	-3.32	2.61	1.93	-3.48
		Max Levels	**4.81**	**3.75**	**-1.58**	**4.65**	**3.59**	**-1.74**	**4.49**	**3.43**	**-1.90**

Expanded Beam Optics

TP1 to TP1' min IL (dB)	TP1' to TP2 min IL (dB)	TP2 to TP3 min IL (dB)	$AOP_{TP1'}$ (dBm)			AOP_{TP2} (dBm)			AOP_{TP3} (dBm), w/c		
			T_{BS} Cold	T_{BS} = 25ºC	T_{BS} = 125ºC	T_{BS} Cold	T_{BS} = 25ºC	T_{BS} = 125ºC	T_{BS} Cold	T_{BS} = 25ºC	T_{BS} = 125ºC
1.37	0.21	0.21	3.83	2.47	-3.02	3.61	2.26	-3.23	3.40	2.05	-3.44
1.37	0.21	0.21	3.40	2.14	-3.09	3.18	1.93	-3.30	2.97	1.71	-3.52
1.37	0.21	0.21	4.81	3.52	-3.16	4.60	3.31	-3.38	4.38	3.10	-3.59
1.37	0.21	0.21	4.69	3.49	-3.31	4.48	3.28	-3.53	4.27	3.06	-3.74
1.37	0.21	0.21	2.55	1.20	-1.84	2.34	0.98	-2.05	2.13	0.77	-2.27
1.37	0.21	0.21	3.90	2.71	-1.58	3.69	2.50	-1.79	3.47	2.28	-2.00
1.37	0.21	0.21	4.81	3.75	-1.58	4.60	3.54	-1.79	4.38	3.33	-2.00
1.37	0.21	0.21	3.90	2.82	-3.09	3.69	2.61	-3.30	3.47	2.39	-3.52
1.37	0.21	0.21	2.93	2.25	-3.16	2.72	2.03	-3.38	2.50	1.82	-3.59
		Max Levels	**4.81**	**3.75**	**-1.58**	**4.60**	**3.54**	**-1.79**	**4.38**	**3.33**	**-2.00**

Eye safety limits

Eye safety limits: BC, 850 nm, Class 1

Class 1, 1M Emission Limits for range

700 nm to 1400 nm

Condition		
Condition	1	= Telescope
	2	= Microscope
	3	= Naked eye or Low power Magnifiers

Class 1 Hazard	0.979	PASS
Class 1M Hazard	0.307	PASS

Parameter	Wavelength 1			Units
λ =	850			nm
Power =	4.0			dBm
NA =	0.185			-
N_fiber_vert	1.0			-
N_fibers_horiz	1.0			-
Spacing_y	0.25			*mm*
Spacing_x	0.25			*mm*
Source dia. (one)	0.05			*mm*
condition	1	2	3	
d_0 =	50.0	3.5	7.0	*mm*
L =	2000	14	100	*mm*
worst_comb_y	1.00	1.00	1.00	
worst_comb_x	1.00	1.00	1.00	
Source count	1.00	1.00	1.00	
alpha (worst)	1.50	3.57	1.50	*mrad*
T2	10.00	10.50	10.00	*sec*
d_{63} =	442.94	3.10	22.15	*mm*
C_4 =	1.995	1.995	1.995	
C_6 =	1.00	2.38	1.00	
C_7 =	1.0	1.0	1.0	-
η =	0.013	0.720	0.095	-

AEL per Class/condition

Class 1 AEL	0.778	1.848	0.778	*mW*
Max permissible power for hazard 1:	61.458	2.565	8.185	*mW*
Total Power per wavelength per condition:	2.512	2.512	2.512	*mW*
Hazard per wavelength per conditions Class 1 =	0.0409	0.9794	0.3069	-
Maximum Level per wavelength — Class 1	0.979			
Maximum Level per wavelength — Class 1M	0.307			

Eye safety limits: BC, 850 nm, Class 1M

Class 1, 1M Emission Limits for range

700 nm to 1400 nm

Condition		
Condition	1	= Telescope
	2	= Microscope
	3	= Naked eye or Low power Magnifiers

Class 1 Hazard	3.169	EXCEEDED
Class 1M Hazard	0.993	PASS

Parameter	Wavelength 1			Units
λ =	850			nm
Power =	9.1			dBm
NA =	0.185			-
N_fiber_vert	1.0			-
N_fibers_horiz	1.0			-
Spacing_y	0.25			*mm*
Spacing_x	0.25			*mm*
Source dia. (one)	0.05			*mm*
condition	1	2	3	
d_0 =	50.0	3.5	7.0	*mm*
L =	2000	14	100	*mm*
worst_comb_y	1.00	1.00	1.00	
worst_comb_x	1.00	1.00	1.00	
Source count	1.00	1.00	1.00	
alpha (worst)	1.50	3.57	1.50	*mrad*
T2	10.00	10.50	10.00	*sec*
d_{63} =	442.94	3.10	22.15	*mm*
C_4 =	1.995	1.995	1.995	
C_6 =	1.00	2.38	1.00	
C_7 =	1.0	1.0	1.0	-
η =	0.013	0.720	0.095	-

AEL per Class/condition

Class 1 AEL	0.778	1.848	0.778	*mW*
Max permissible power for hazard 1:	61.458	2.565	8.185	*mW*
Total Power per wavelength per condition:	8.128	8.128	8.128	*mW*
Hazard per wavelength per conditions Class 1 =	0.1323	3.1693	0.9931	-
Maximum Level per wavelength — Class 1	3.169			
Maximum Level per wavelength — Class 1M	0.993			

Eye safety limits: BC, 980 nm, Class 1

Class 1, 1M Emission Limits for range

700 nm to 1400 nm

Condition		
Condition	1	= Telescope
	2	= Microscope
	3	= Naked eye or Low power Magnifiers

Class 1 Hazard	0.979	PASS
Class 1M Hazard	0.307	PASS

Parameter	Wavelength 1			Units
λ =	980			nm
Power =	6.6			dBm
NA =	0.185			-
N_fiber_vert	1.0			-
N_fibers_horiz	1.0			-
Spacing_y	0.25			*mm*
Spacing_x	0.25			*mm*
Source dia. (one)	0.05			*mm*
condition	1	2	3	
d_0 =	50.0	3.5	7.0	*mm*
L =	2000	14	100	*mm*
worst_comb_y	1.00	1.00	1.00	
worst_comb_x	1.00	1.00	1.00	
Source count	1.00	1.00	1.00	
alpha (worst)	1.50	3.57	1.50	*mrad*
T2	10.00	10.50	10.00	*sec*
d_{63} =	442.94	3.10	22.15	*mm*
C_4 =	3.631	3.631	3.631	
C_6 =	1.00	2.38	1.00	
C_7 =	1.0	1.0	1.0	-
η =	0.013	0.720	0.095	-

AEL per Class/condition

Class 1 AEL	1.416	3.362	1.416	*mW*
Max permissible power for hazard 1:	111.835	4.667	14.894	*mW*
Total Power per wavelength per condition:	4.571	4.571	4.571	*mW*
Hazard per wavelength per conditions Class 1 =	0.0409	0.9794	0.3069	-
Maximum Level per wavelength — Class 1	0.979			
Class 1M	0.307			

Eye safety limits: BC, 980 nm, Class 1M

KDPOF Knowledge Development

Class 1, 1M Emission Limits for range

700 nm to 1400 nm

Condition		
Condition	1	= Telescope
	2	= Microscope
	3	= Naked eye or Low power Magnifiers

Class 1 Hazard	3.169	EXCEEDED
Class 1M Hazard	0.993	PASS

Parameter	Wavelength 1			Units
λ =	980			nm
Power =	11.7			dBm
NA =	0.185			-
N_fiber_vert	1.0			-
N_fibers_horiz	1.0			-
Spacing_y	0.25			*mm*
Spacing_x	0.25			*mm*
Source dia. (one)	0.05			*mm*
condition	1	2	3	
d_0 =	50.0	3.5	7.0	*mm*
L =	2000	14	100	*mm*
worst_comb_y	1.00	1.00	1.00	
worst_comb_x	1.00	1.00	1.00	
Source count	1.00	1.00	1.00	
alpha (worst)	1.50	3.57	1.50	*mrad*
T2	10.00	10.50	10.00	*sec*
d_{63} =	442.94	3.10	22.15	*mm*
C_4 =	3.631	3.631	3.631	
C_6 =	1.00	2.38	1.00	
C_7 =	1.0	1.0	1.0	-
η =	0.013	0.720	0.095	-

AEL per Class/condition

Class 1 AEL	1.416	3.362	1.416	*mW*
Max permissible power for hazard 1:	111.835	4.667	14.894	*mW*
Total Power per wavelength per condition:	14.791	14.791	14.791	*mW*
Hazard per wavelength per conditions Class 1 =	0.1323	3.1693	0.9931	-

Maximum Level per wavelength	**Class 1**	**3.169**
	Class 1M	**0.993**

Eye safety limits: EBO, 850 nm, Class 1 / 1M

Class 1, 1M Emission Limits for range

700 nm to 1400 nm

Condition		
Condition	1	= Telescope
	2	= Microscope
	3	= Naked eye or Low power Magnifiers

Class 1 Hazard	0.998	PASS
Class 1M Hazard	0.998	PASS

Parameter	Wavelength 1			Units
λ =	850			nm
Power =	-1.1			dBm
NA =	0.0001			-
N_fiber_vert	1.0			-
N_fibers_horiz	1.0			-
Spacing_y	0.25			*mm*
Spacing_x	0.25			*mm*
Source dia. (one)	0.05			*mm*
condition	1	2	3	
d_0 =	50.0	3.5	7.0	*mm*
L =	2000	14	100	*mm*
worst_comb_y	1.00	1.00	1.00	
worst_comb_x	1.00	1.00	1.00	
Source count	1.00	1.00	1.00	
alpha (worst)	1.50	3.57	1.50	*mrad*
T2	10.00	10.50	10.00	*sec*
d_{63} =	0.24	0.00	0.01	*mm*
C_4 =	1.995	1.995	1.995	
C_6 =	1.00	2.38	1.00	
C_7 =	1.0	1.0	1.0	-
η =	1.000	1.000	1.000	-

AEL per Class/condition

Class 1 AEL	0.778	1.848	0.778	*mW*
Max permissible power for hazard 1:	0.778	1.848	0.778	*mW*
Total Power per wavelength per condition:	0.776	0.776	0.776	*mW*
Hazard per wavelength per conditions Class 1 =	0.9976	0.4202	0.9976	-
Maximum Level per wavelength — Class 1	0.998			
Maximum Level per wavelength — Class 1M	0.998			

Eye safety limits: EBO, 980 nm, Class 1 / 1M

Class 1, 1M Emission Limits for range

700 nm to 1400 nm

Condition		
Condition	1	= Telescope
	2	= Microscope
	3	= Naked eye or Low power Magnifiers

Class 1 Hazard	0.998	PASS
Class 1M Hazard	0.998	PASS

Parameter	Wavelength 1			Units
λ =	980			nm
Power =	1.5			dBm
NA =	0.0001			-
N_fiber_vert	1.0			-
N_fibers_horiz	1.0			-
Spacing_y	0.25			*mm*
Spacing_x	0.25			*mm*
Source dia. (one)	0.05			*mm*
condition	1	2	3	
d_0 =	50.0	3.5	7.0	*mm*
L =	2000	14	100	*mm*
worst_comb_y	1.00	1.00	1.00	
worst_comb_x	1.00	1.00	1.00	
Source count	1.00	1.00	1.00	
alpha (worst)	1.50	3.57	1.50	*mrad*
T2	10.00	10.50	10.00	*sec*
d_{63} =	0.24	0.00	0.01	*mm*
C_4 =	3.631	3.631	3.631	
C_6 =	1.00	2.38	1.00	
C_7 =	1.0	1.0	1.0	-
η =	1.000	1.000	1.000	-

AEL per Class/condition

Class 1 AEL	1.416	3.362	1.416	*mW*
Max permissible power for hazard 1:	1.416	3.362	1.416	*mW*
Total Power per wavelength per condition:	1.413	1.413	1.413	*mW*
Hazard per wavelength per conditions Class 1 =	0.9976	0.4202	0.9976	-
Maximum Level per wavelength — Class 1	0.998			
Class 1M	0.998			

Eye safety limits — conclusions

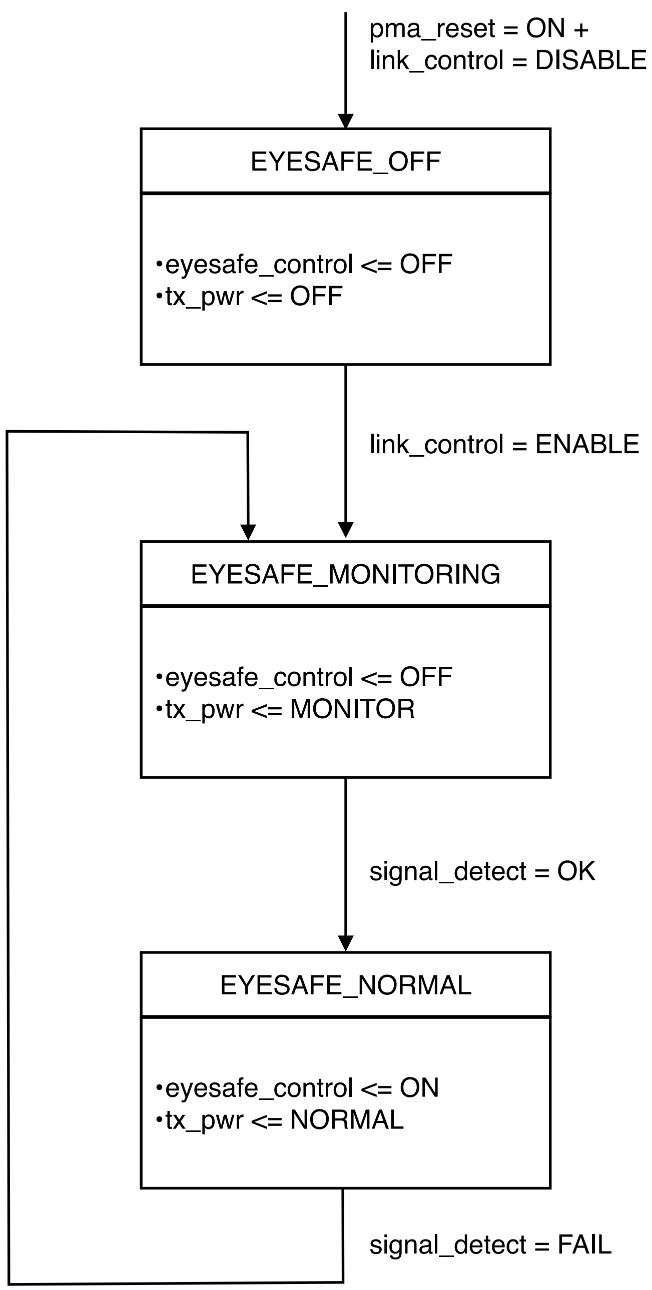
- For BC, where divergent emission condition exists, there are two different limits for Class 1 and Class 1M
  - Class 1M limit is 5.1 dB higher
  - In automotive —> Laser Class 1
- For EBO, the limits are the same for Class 1 and Class 1M because the collimated emission condition
- The use of longer wavelength relaxes the eye safety limits: the limit at 980 nm is 2.6 dB higher than in case of 850 nm
- Class 1 limits for EBO are 5.1 dB more stringent than for BC
- Considering the minimum T_{BS} = 25ºC where connectors can be manipulated, BC meets the Class 1 limits
- Steps need to be taken to get EBO to comply with Class 1 and Class 1M limits

General method to meet eye safety limits

Options to meet eye safety limits

- Option 1: Connectors (transceiver and inline connections) with shutter. This is an expensive solution in a cost driven application as automotive
- Option 2: One time locked connectors that would need a special tool to disconnect
  - Only trained personnel can handle the connectors
  - Connectors locked in production line
  - This solution is very expensive
- Option 3: Eye safety power state in the TX when no receive signal is detected
  - Lowest cost solution because no special mechanical countermeasures have to be implemented in the connector
  - Connectors **have to be duplex** to ensure that both transmission paths of the link are opened at the same time by design
- Options 1 and 2 are discarded because cost
- Next slides elaborate in detail the Option 3

State diagram for eye safety control



- **eyesafe_control:** variable set by the PMA eye safety control state diagram to control the operation of the PMA TX and RX.
  (Modify PHY TX control and PHY RX control state diagrams to respond to open-ended eyesafe_control = OFF)
  Values:
  - OFF: PMA is disabled
  - ON: PMA is enabled
- **tx_pwr:** controls the PMD transmitter power
  Values:
  - OFF: PMD TX does not generate optical signal ($AOP_{TP1'}$ = 0 mW)
  - MONITOR: PMD TX generates optical signal with $AOP_{TP1'}$ below eye safety limits and AOP_{TP2} higher than a threshold ($AOP_{TP2-MON-MIN}$) to guarantee signal_detect = OK is produced in the link partner
  - NORMAL: PMD TX generates optical signal as needed for reliable link operation and that may overpass the eye-safety limits
- **signal_detect:** parameter indicating whether the PMD is detecting average optical power over a threshold at the receiver or not.
  - OK: PMD is detecting average optical power over a threshold
  - FAIL: PMD is detecting average optical power below a threshold

Thresholds to be defined in the PMD

- $AOP_{TP3\text{-}WU}$: if $AOP_{TP3} > AOP_{TP3\text{-}WU}$, then the parameter signal_detect = OK
- $AOP_{TP3\text{-}SD}$: if $AOP_{TP3} < AOP_{TP3\text{-}SD}$, then the parameter signal_detect = FAIL
- For $AOP_{TP3\text{-}SD} \leq AOP_{TP3} \leq AOP_{TP3\text{-}WU}$, the value of signal_detect is unspecified (uncertainty range)
- $AOP_{TP2\text{-}MON\text{-}MIN}$: the min AOP at TP2 to guarantee signal_detect = OK in the link partner considering the max insertion loss of the channel
- $AOP_{MDI\text{-}MON\text{-}MAX}$: the max AOP at the MDI that meets eye-safety limits for a specific launching condition.
- Launching condition has to be defined and it depends on BC or EBO MDI
- $t_{TX\text{-}NORMAL\text{-}to\text{-}MON\text{-}MAX}$: max time between signal_detect OK to FAIL transition and tx_pwr NORMAL to MON transition
  - It is implementable to be < 100 μs.

Conclusion

- AOP measurements at TP1 have been presented for several characterized VCSEL in cold, room and hot temperatures
- Based on realistic optical coupling design, AOP at TP1', TP2 and TP3 have been calculated for BC and EBO connectivity
- Eye-safety limit have been calculated for Class 1 and Class 1M considering BC and EBO
- A simple general method for eye safety control has been proposed that allows to meet eye-safety limit regardless the used optical connectivity, BC or EBO

Thank you!