Co-Packaging Framework Document

OIF-Co-Packaging-FD-01.0

February 3, 2022

Implementation Agreement created and approved

OIF

www.oiforum.com

The OIF is an international non-profit organization with over 100 member companies, including the world's leading carriers and vendors. Being an industry group uniting representatives of the data and optical worlds, OIF's purpose is to accelerate the deployment of interoperable, cost-effective and robust optical internetworks and their associated technologies. Optical internetworks are data networks composed of routers and data switches interconnected by optical networking elements.

With the goal of promoting worldwide compatibility of optical internetworking products, the OIF actively supports and extends the work of national and international standards bodies. Working relationships or formal liaisons have been established with CFP-MSA, COBO, EA, ETSI NFV, IEEE 802.3, IETF, INCITS T11, ITU SG-15, MEF, ONF.

For additional information contact:
OIF
5177 Brandin Ct, Fremont, CA 94538
510-492-4040 F info@oiforum.com

www.oiforum.com

Working Group: **Physical Link Layer Working Group**

TITLE: **Co-Packaging Framework Document**

SOURCE:

TECHNICAL EDITOR
Kenneth Jackson
Sumitomo Electric
2355 Zanker Rd.
San Jose, CA 95131
Phone: +1-626-506-9975
Email: kjackson@sei-device.com

PLL WORKING GROUP CHAIR
David R. Stauffer, Ph. D.
Kandou Bus, S.A.
QI-I
1015 Lausanne Switzerland
Phone: +1 802 316 0808
Email: david@kandou.com

PLL WORKING GROUP – CO-PACKAGING VICE CHAIR
Jeff Hutchins
Ranovus
Phone: +1 408 627 8036
Email: jeff@ranvous.com

ABSTRACT: This Framework Document addresses the application spaces and relevant technology considerations for co-packaging of optical and electrical communication interfaces with one or more ASICs. A primary objective of this effort is to identify new opportunities for interoperability standards for possible future work in the OIF or other standards organizations.

1 Table of Contents

2 List of Figures

3 List of Tables

4 Document Revision History

Working Group: Physical and Link Layer Working Group

SOURCE:

TECHNICAL EDITOR
Kenneth Jackson
Sumitomo Electric
2355 Zanker Rd.
San Jose, CA 95131
Phone: +1-626-506-9975
Email: kjackson@sei-device.com

PLL WORKING GROUP CHAIR
David R. Stauffer, Ph.D.
Kandou Bus, SA
QI-I
1015 Lausanne, Switzerland
Phone: +1-802-316-0808
Email: david@kandou.com

DATE: February 3, 2022

Document	Date	Revisions/Comments
OIF-Co-Packaging-FD-01.0	Feb 03, 2020	Initial document release

5 Introduction

Next generation datacenter switching networks and high-performance computing, such as machine-learning and artificial intelligence, are increasingly challenged by a combination of high-power dissipation and the need for high bandwidth I/O escape from the ASICs enabling these applications. Scaling of current architectures suggest that next generation systems will challenge the cooling capabilities of these systems. New architectures and new technology implementations are required if the desired performance levels are to be achieved.

Co-packaging, where optical or electrical communications devices are attached on the same first-level substrate as the host ASIC (Figure 1), is expected to provide high bandwidth interconnects with significant power savings. By locating the optical engine in close proximity to the Host ASIC, the high-speed electrical channel losses and impedance discontinuities can be minimized, thus enabling the use of higher speed, lower power, off-chip I/O drivers.

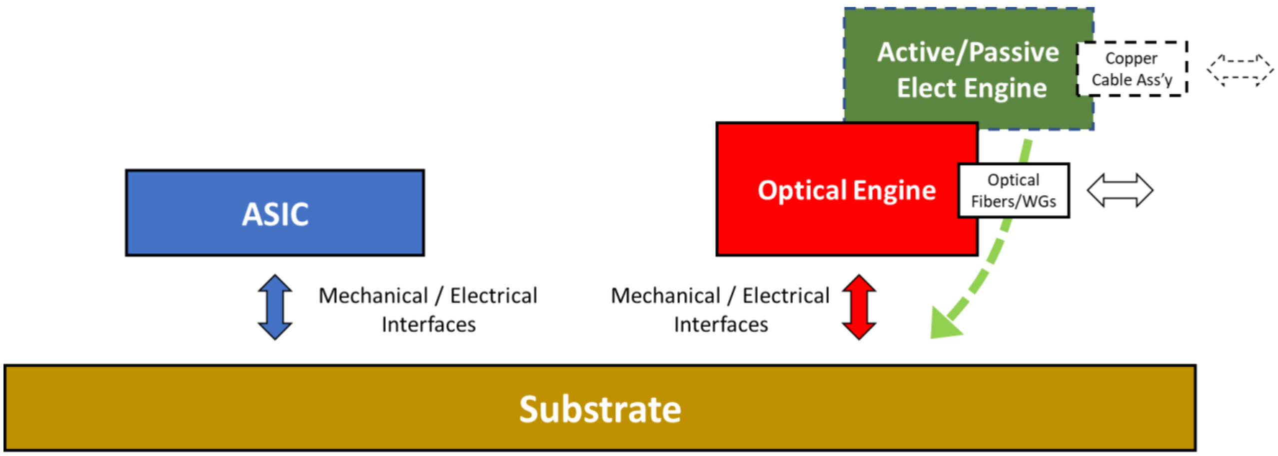


Figure 1: Co-Packaging implementation.

Figures 2a – d show some specific use-cases with different packaging arrangements for engines and ASICs. The Co-Packaging Assembly (CPA) is a Multi-Chip Module (MCM) with either socketed or soldered ASIC and Optical Engines (OE) or Electrical Engines (EE) placed onto a high-performance substrate.

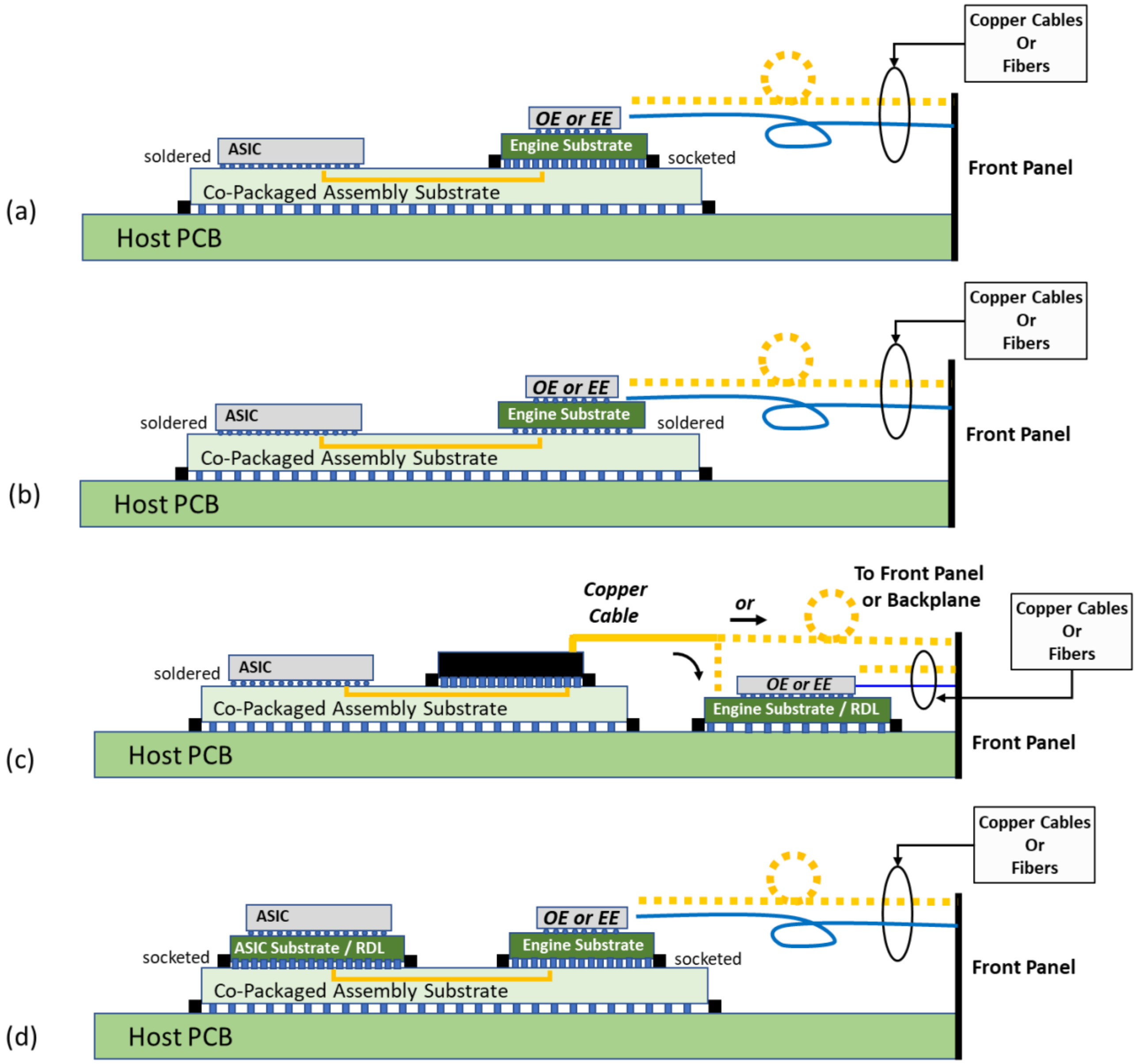


Figure 2: Example use-cases for Co-Packaged optical or electrical engines.

Figure 2c shows a use case where the engine locations are populated with a passive Copper Cable Assembly (CCA) to connect to close-proximity transceivers (such as coherent) which may not fit into the OE or EE footprint for co-packaging. The CCA could also be used to connect with an on-board optical or electrical engine, or with a front-panel module.

Figure 2d shows a use-case where a packaged ASIC (ASIC die plus ASIC substrate/RDL) and engine are attached to a common substrate using sockets which facilitate the attachment and removal of the devices during assembly and rework. This arrangement is referred to as socketed, “near-package optics” (NPO).

The purpose of this Framework Document is to identify some of the key applications and their requirements for which co-packaging implementations may provide significant benefits. This paper will also discuss some of the issues associated with optical and electrical co-packaging and identify opportunities and develop industry consensus to pursue *interoperability standards*. It is expected that this Framework project will result in follow-on standardization activities at the OIF or other appropriate standard bodies.

6 Applications Overview

Three applications have been identified as benefitting from co-packaging (Figure 3):

1) Data center networking, which typically include Ethernet NICs and switches connecting servers and storage devices,
2) AI training / machine learning, where specialized high-performance graphics or tensor processors are tightly coupled to process (learn) from examples (training data) to provide predictions and/or decisions and
3) System disaggregation, where the processing, memory and storage functions are shared among multiple compute nodes to increase usage efficiency.

Each application contains two communications endpoints, a Switching Node, connected to another Switch node or an End-node. They each have different requirements and operating environments. These applications are expected to drive the need for even higher bandwidth interconnects with lower latency and lower power dissipation than today's implementations. Current approaches (those typically employing pluggable optical transceivers or passive copper cables) will have difficulty meeting these requirements and next generation systems require new architectures and technologies. By co-packaging the communications interfaces (e.g., optical or electrical engines) in close proximity to the ASIC, high data-throughput interconnects with lower power and lower latency are possible.

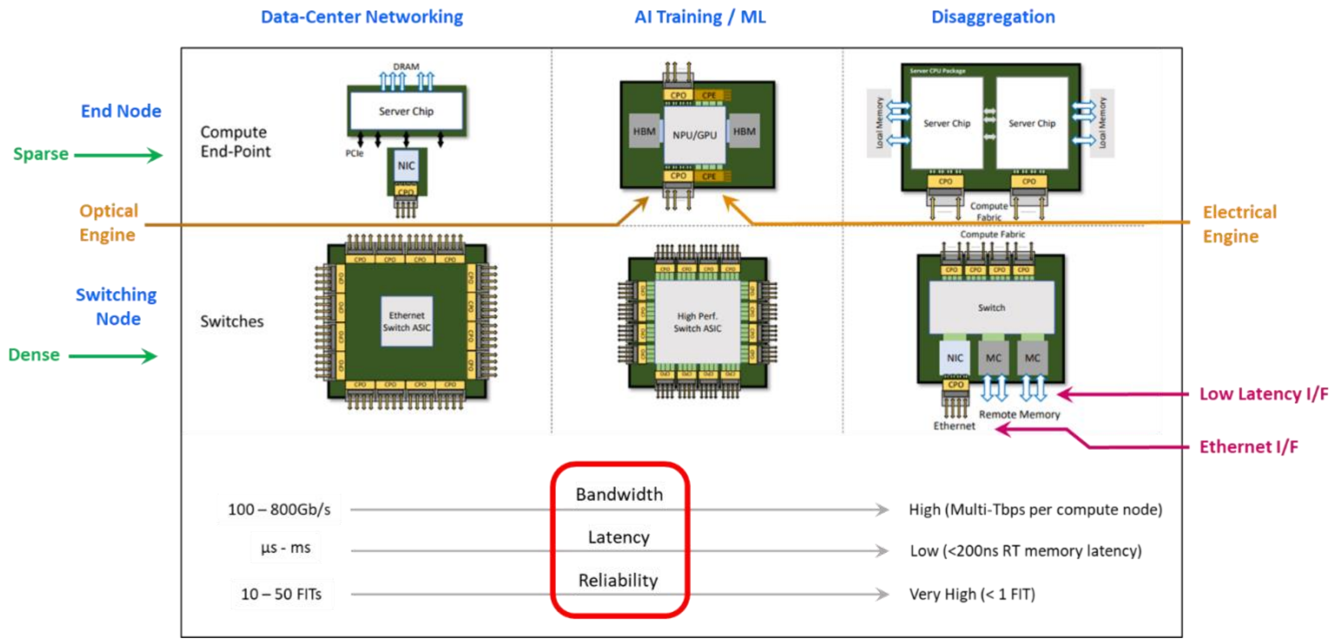


Figure 3: Applications potentially benefitting from co-packaging.

These co-packaged applications may use a variety of electrical interface standards such as XSR, LR, PCIe, or even wide interfaces such as AIB. Some of electrical interfaces will be low latency typically implemented with no FEC or perhaps a very low latency FEC code.

Although these applications can have different overall requirements, the insertion loss of the optical interconnects supporting these applications can be similar. Figure 4 shows co-packaged optical engines with multiples of base lane data-rates of 100Gb/s and an optical insertion loss budget of 4dB (for single-mode fiber-based implementations) for use in data center networking and AI Training with Ethernet protocols. Short reach data center networking applications may have a loss budget of 1.8dB (for multi-mode fiber-based implementations). For some of the AI Training and disaggregated systems, where the resources being shared are not bandwidth intensive the base lane data-rate is expected to be lower (e.g., 32Gb/s NRZ interfaces based on PCIe gen 5) together with a lower-latency protocol such as CXL. Memory disaggregation, on the other hand, requires transfers of large data blocks between many endpoints (memory) and processors. Large radix switches with low latency will be needed and all-optical switching approaches may provide the desired performance. As a result, the optical insertion loss budget increases from 4dB to 8-10dB to accommodate these kinds of implementations.

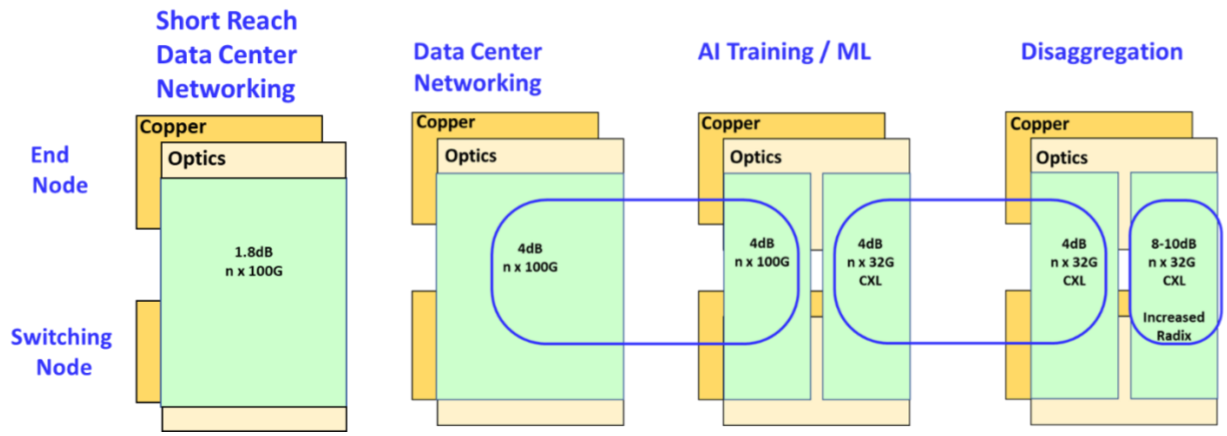


Figure 4: Possible common optical interconnect requirements for the indicated applications and associated endpoints.

Table 1 shows some other required features for these applications, including energy efficiency, type of engine at the end node, number of engines per end node and switch node as well as engine reliability. Cells without values are expected to be added when the requirements are better defined.

Table 1: Required features for the applications considered. ***(Note: Grayed cells to be completed when system requirements are better defined.)***

	Application					
	Data Center Switching Network (including Short Reach)	HPC / AI	AI Training / ML		Disaggregation	Disaggregation (Memory)
	Ethernet			CXL		
	Point-to-point		Point-to-point		Point-to-point	Increased Radix
Energy Efficiency[1]	≤ 15 pJ/b	≤ 15 pJ/b	5-10 pJ/b	5-10 pJ/b	5-10 pJ/b	5-10 pJ/b
Engine End Node	Pluggable or CoPkg 4 x 106G	CoPkg 32 x 106G	CoPkg 32 x 106G	CoPkg 32 x 32G	CoPkg 32 x 32G	CoPkg 32 x 32G
Engines per End Node	1x	2x to 4x	4x to 8x		2x to 4x	2x to 4x
Engine per Switch Node	16x	16x				
Switch Capacity	≤ 51.2T	≤ 51.2T				
Engine Reliability[2]	10 FIT (3.2T)	10 FIT (3.2T)	10 FIT (3.2T)			
3.2Tb/s Laser Source Reliability[3]	50 FIT (3.2T)	50 FIT (3.2T)	50 FIT (3.2T)			
Engine and Laser Source Lifetime	6 years	6 years	6 years			

[1] Energy efficiency estimates include engine-side host electrical interface, CDR, PIC components, and laser source. Excludes switch-side. Assumes XSR electrical interface for Ethernet co-packaged optics applications.
[2] Contribution to reliability from an engine excluding contribution from lasers
[3] Contribution to reliability from lasers excluding contribution from engine.

Table 2 shows the attributes for the applications' endpoints and Table 3 shows the expected signaling formats and protocols for the different applications.

Table 2: Attributes for the applications communication's links endpoints.

	Location	
	Switch Node (Dense)	**End Node (sparse)**
Electrical I/F	High speed (density)	High Speed Wide
Thermal	Air Cooling Liquid Cooling	Air Cooling Liquid Cooling
Optical	Higher Fiber Count	Lower Fiber Count
Lasers	Internal External	Internal External
Optical Engine Form Factor	Co-packaged	Co-packaged Module

Table 3: Signaling formats and protocols for the specified applications.

Signaling			
MAC	**Electrical**	**Optical (Point-to-point)**	**Increased Radix**
Ethernet • 100GbE • 400GbE	- CEI-112G-XSR at 103 or 106 Gb/s per lane - CEI-112G-LR at 106 Gb/s per lane -CEI-224G (TBD) at up to 224 Gb/s per lane	4dB - 100G-CWDM4-OCP - 100G-PSM4 - 400GBASE-FR4/DR4 1.8dB: -100GBASE-VR/SR 400GBASE-VR4/SR4	N/A
CXL[4] • n x 32GT/s	n x 4 x 32G NRZ Wide I/F w/ optional FEC	4dB CXL DR/FR (potentially MMF solutions)	8-10dB CXL xWDM/PSM

In the remainder of this document, the data center networking application will be the primary focus describing possible co-packaging solutions for a 51.2Tb/s Ethernet switch in a 1RU configuration.

7 Potential Interfaces for Interoperability Standards

7.1 Introduction

In this section, the potential interfaces for interoperability standards, including electrical, optical, and mechanical interfaces along with environmental operating conditions are described.

7.2 Electrical Interfaces

As mentioned earlier, co-packaging is expected to provide high bandwidth interconnects with significant power savings. By locating these communications interfaces (engines) in close proximity to the ASICs,

[4] CXL is used here as an example of a short-range device interconnect providing high-bandwidth, low latency connectivity. Other interconnect protocols with similar capabilities may be suitable.

the high-speed electrical channel losses and impedance discontinuities can be minimized, thus enabling the use of higher speed, lower-power, off-chip I/O drivers from the ASIC. Some of the electrical interfaces being considered are described in Figure 5 through Figure 8. The "re-timed" interface shown in Figure 5 is expected to utilize the CEI-112G-XSR-PAM4 Extra Short Reach Interface implementation agreement currently being developed. The transmit (Tx) and receive (Rx) functions contained in the host ASIC side of the interface will have sufficient capabilities (e.g., drive amplitude, equalization, etc.) to enable low error rate communications between the ASIC and optical engine over approximately 50mm of 1st level packaging substrate, including package parasitics from the ASIC and the optical engine assembly. Test points, test methodologies and test criteria will be part of an IA associated with these component interfaces in future projects.

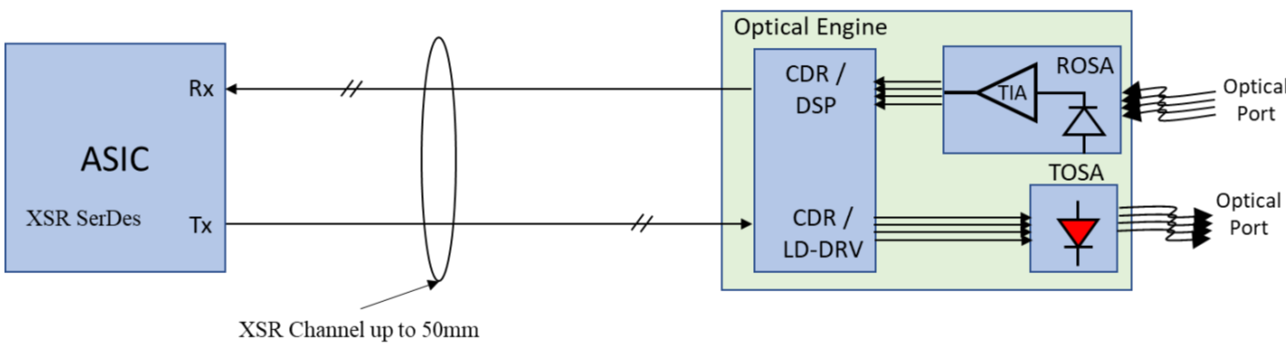


Figure 5: Re-timed. Note: Trace length and SerDes type informational. Achievable distance depends on channel impairments including insertion loss, crosstalk, package parasitics and impedance discontinuities.

Figure 6 shows another potential electrical interface, "Linear Amplified". In this case, the CDR/DSP function in the engine is eliminated (to reduce power dissipation) but because the modulation format may be PAM4, the drive signal must be relatively linear without amplitude compression. In addition, the SerDes in the ASIC must compensate for the entire link, from SerDes Tx to SerDes Rx. As a result, the Tx and Rx functions in the ASIC must have greater capability (e.g., more amplification and peaking) than similar functions in the "Re-Timed" interface shown in Figure 5.

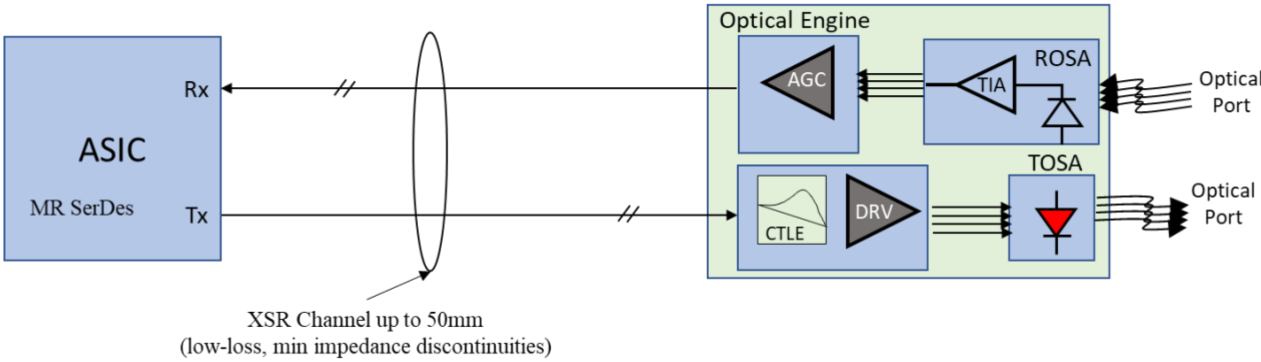


Figure 6: Linear amplified. Note: Trace length and SerDes type informational. Achievable distance depends on channel impairments including insertion loss, crosstalk, package parasitics and impedance discontinuities.

Another interface option, shown in Figure 7, is referred to as "Half-retimed". Here one-half (either Tx or Rx) of the engine and ASIC communication is re-timed, with the other half utilizing a linear-amplified approach. This approach combines implementations from Figure 5 and Figure 6.

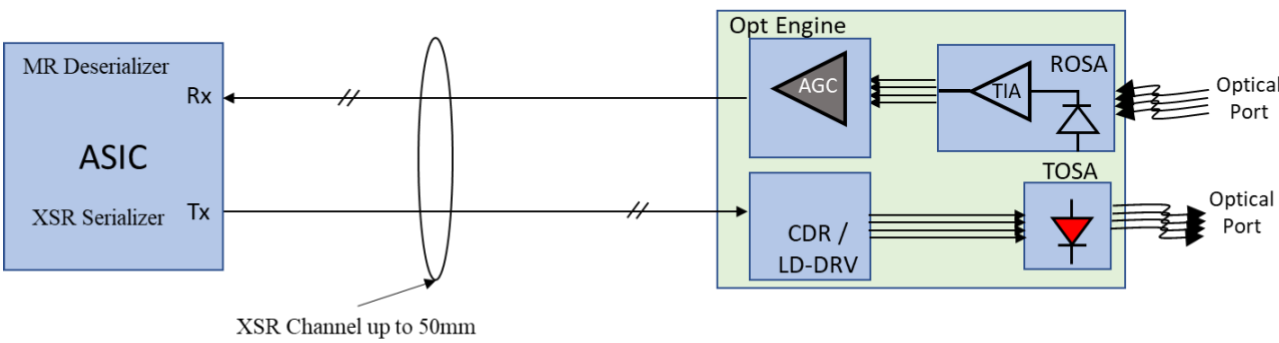


Figure 7: Half-retimed. Note: Trace length and SerDes type informational. Achievable distance depends on channel impairments including insertion loss, crosstalk, package parasitics and impedance discontinuities.

The last host ASIC to engine interface considered is shown in Figure 8, "Direct Drive". Here the engine functionality is simplified leaving only those functions necessary to support a linear optical communications channel (due to a PAM4 modulation format assumption). The host ASIC contains the necessary capabilities to drive the optical signals (e.g., sufficient amplitude capabilities to drive the optical modulator or laser) as well as equalization on the receive path to remove impairments imposed by the optical and electrical signal paths and enable error-free communications. Trace lengths for this approach are expected to be much shorter than the previous interfaces described due to the desire to eliminate DSP/CDR and amplification functionality. Again, for this electrical interface, test points, test methodologies and test criteria would be included in a future IA.

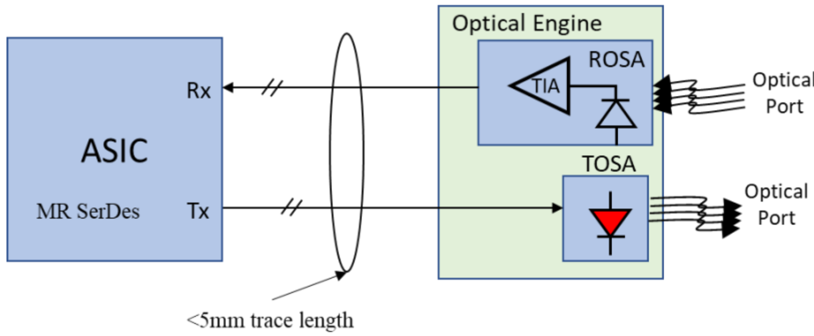


Figure 8: Direct drive. Note: Trace length and SerDes type informational. Achievable distance depends on channel impairments including insertion loss, crosstalk, package parasitics and impedance discontinuities.

For some of the use-cases shown in Figures 2a-d, the XSR electrical interface specification may be insufficient due to the increased channel loss and impedance discontinuities. In these cases, an enhanced electrical interface specification may be required (e.g. CEI-112G-XSR+-PAM4), having greater transmit voltage amplitude swings, and increased equalizer capabilities.

7.2.1 Electrical Footprint

The overall size of the co-packaged optical or electrical engine will be determined by the total bandwidth capability of the engine, wiring density on the engine and CPA substrate, the physical size of the optical fiber attachment interface and the thermal management approach. The engine is attached to the CPA substrate using a soldered ball-grid or copper pillar array or an array type removable connection (e.g., land-grid array). In the latter case, a retention mechanism is required which consumes CPA substrate area and can limit the achievable density.

Some of the trade-offs between a solder reflow attach and socket attached are shown in Table 4.

Table 4: Tradeoffs between solder reflow and socket attach approaches for co-packaged engines.

Criteria	Solder Reflow	Socket
Configurability	Requires Reflow compatible components. Enable Surface mount technology of optical engine.	Mountable, expandable to non-reflow application.
Electrical Performance / signal integrity	Can be close to optimal	Can be excellent
Footprint	Highest Density	Requires Clamping/Retention Mechanism
Rework	Limited and Yield Loss	Yes, but access limited in field
Large number of CPO engine / Complex System in Package	High count integration yield loss	Complexity enabler
Thermal	Conventional approaches	attached with Retention hardware

7.2.2 Socket Retention Mechanism

When the engine is socketed on the CPA, a mechanical compression mechanism is required to compress the socket interposer and provide good electrical contact. The compression mechanism typically involves using bolts in the four corners surrounding the socket. The socket overhead can be reduced by ganging the socket compression hardware thereby sharing the bolt hardware and improving density.

7.3 Optical Interfaces

Like their pluggable counterparts, optical engines will provide connectivity between switches and servers over single mode or multimode optical fiber. Optical engines that are compliant and interoperable with pluggable module standards and work over installed cabling will have broader market appeal. For Data Center Networking, relevant application standards found in IEEE Ethernet 802.3 include 400GBASE-DR4 (802.3bs) and 400GBASE-FR4 (802.3cu). Short Reach Data Center Networking may use emerging standards like 400GBASE-SR4 and 400GBASE-VR4 (802.3db) to enable low cost and low power optical links.

7.3.1 Light (Laser) Sources

Choosing the optimal laser source is critical to designing a co-packaged optics switch. The optical source may consist of multiple lasers operating at multiple wavelengths (to support FR applications) or a single laser or multiple lasers operating at a single wavelength (to support DR, VR and SR applications). When the optical engine is implemented using silicon photonic technology, the lasers maybe integrated within the engine or located externally as shown in Figure 9. In the external laser case, a high output power continuous wave (cw) optical source is used in conjunction with the modulators to provide a modulated data-stream.

External laser sources (ELS) can improve the reliability of a CPO switch because lasers that have failed may be swapped at the faceplate without removing the switch from operation. In addition, ELS architectures physically separate the switch ASIC from the laser which improves the thermal environment for both. These benefits come at the cost of higher insertion loss. These losses must be compensated by increasing the output power of the ELS. Integrated lasers inside the optical engine have fewer losses to overcome and may operate at lower optical power. VCSEL based optical engines with multimode fibers have the potential to be the lowest cost and lowest power option for co-packaged optics for short reach applications.

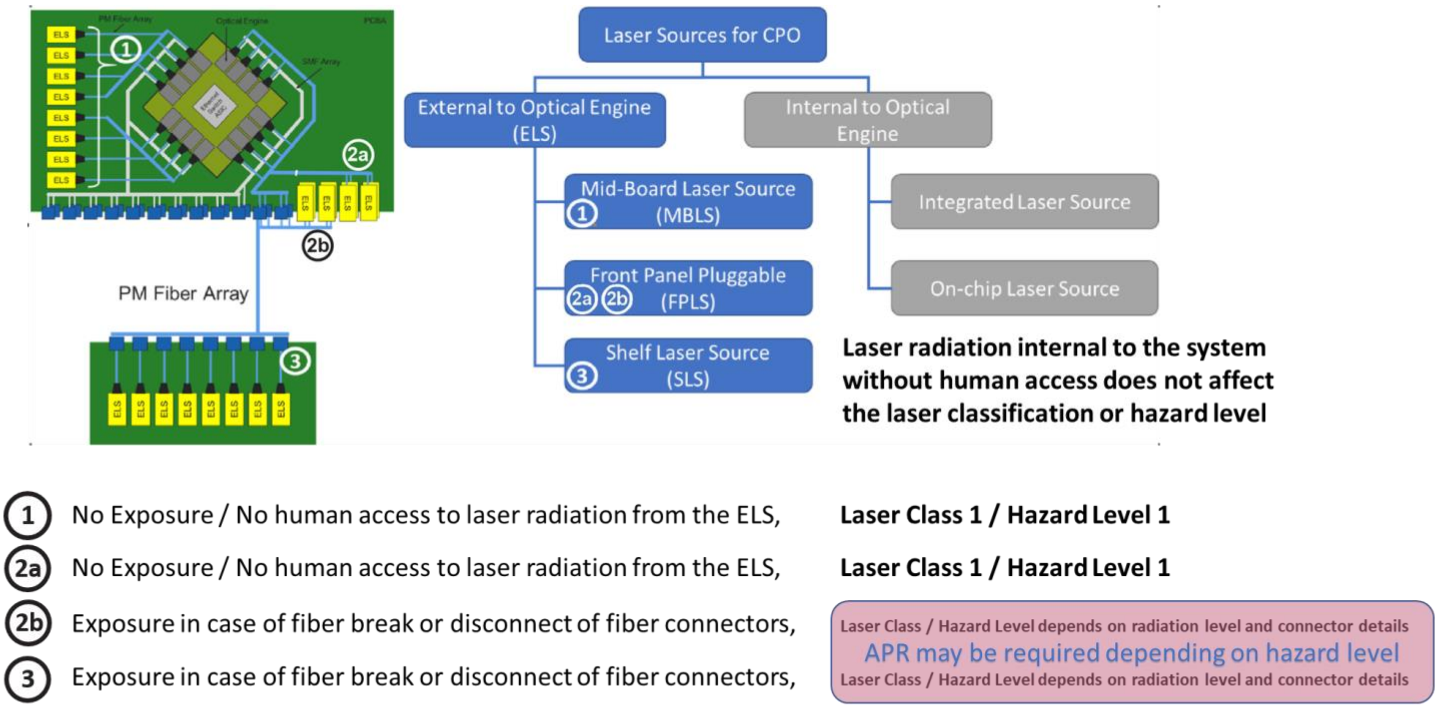


Figure 9: Laser Light Sources: Use-cases, proposed terminology, and associated laser safety considerations. Numbered figure at left corresponds to an external laser source implementation.

When considering an external light source, a single form-factor may contain many lasers. Each laser may supply light to a single or to multiple modulators in the silicon photonic engine. Figure 10 shows various optical power delivery scenarios. For cases where the laser power is high, power splitting can be either inside the ELS, inside the OE, or between the ELS and OE. For cases where the laser power is low or multiple frequencies are needed, power combining can be inside the ELS or inside the OE. Additionally, there are cases where each laser feeds a single lane of the OE transmitter directly.

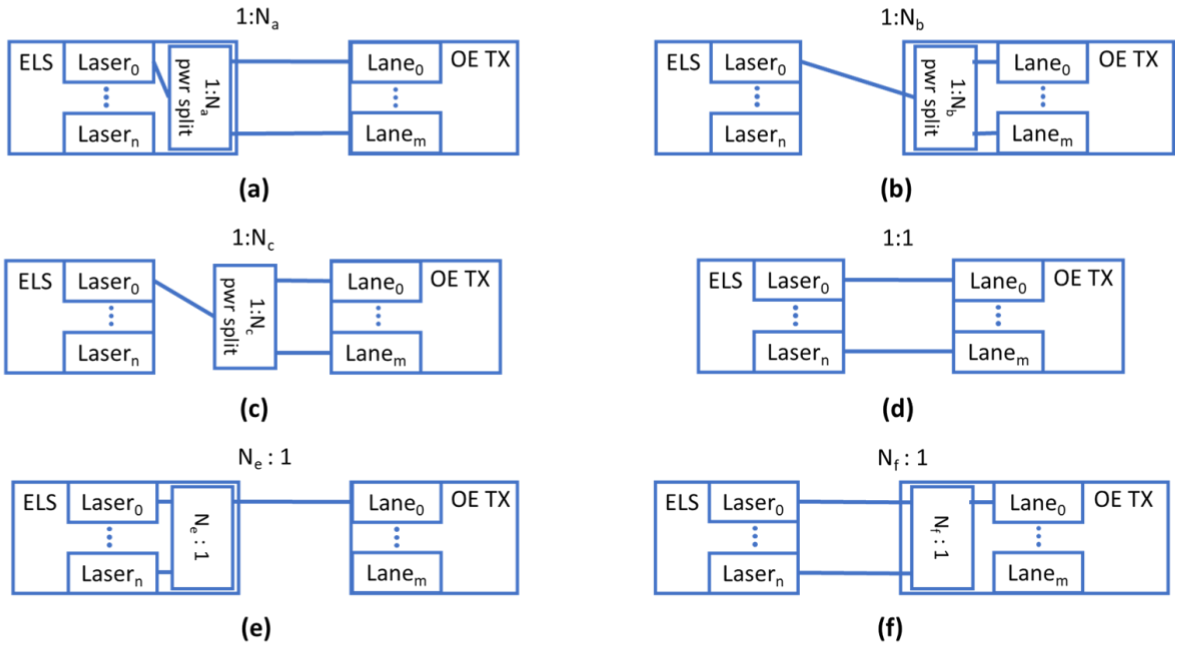


Figure 10: Scenarios for optical power from ELS to OE. (a) 1:Na, (b) 1:Nb, (c) 1:Nc, (d) 1:1, (e) Ne:1, (f) Nf:1..

Future efforts to standardize ELS modules such as an Implementation Agreement in the OIF or an MSA must coordinate the activity with other critical elements of the co-packaging ecosystem. Figure 11 shows the various interdependencies.

Finally, ELSs must be compliant with relevant laser eye safety standards (e.g., IEC 60825-1 2014 (3rd ed) and IEC 60825-2 2021 (ed 4.0)) (see Appendix B: Generalized Laser Safety for MPO-Based ELS Modules). Typically, this means no firmware in the safety system. It should be hardwired, with typically microsecond assertion timings. The approach implemented needs to ensure that mis-connected scenarios are detectable and that the ELS be held at eye safe limit until the optical engine confirms connection integrity. The engine may need to feedback information to the ELS when no light is detected causing the light source to shut down.

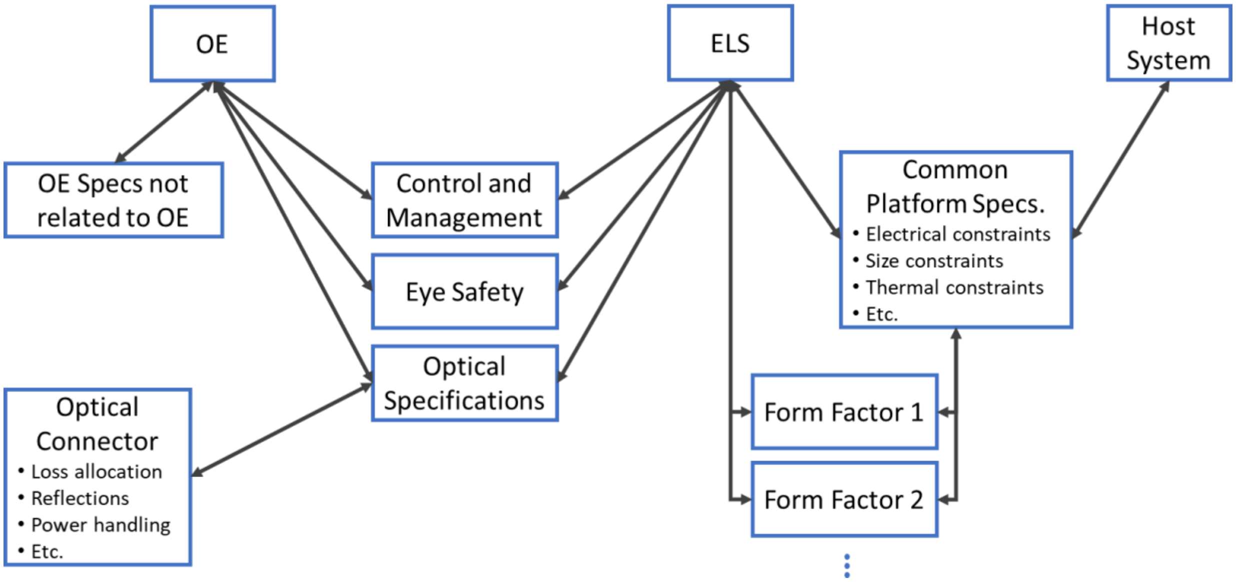


Figure 11: ELS interdependencies on other critical elements of the co-packaging ecosystem.

7.3.2 Pigtailed and/or Connectorized

The engine can be either assembled with pigtail or built-in connector to carry the high-speed data in and out of the engine. The pigtail can consist of a ribbon fiber for high density optical interfaces, or a copper cable assembly for high density electrical interfaces.

By definition, a connectorized engine will require an extra connector to reach the front panel. The pigtailed option may not require an extra connector if the pigtail is long enough to reach the front panel.

The addition of an extra connector increases the insertion loss over an equivalent front-panel pluggable transceiver. The existing high density fiber optic connectors (e.g., MPO) do not meet the size and density constraints and may require a new connector technology to be developed.

7.3.3 Connector or Fiber Exit Location and Size

The fiber or copper cable exit away from the co-packaged assembly (CPA). Copper cables and surface coupled optical engines may need additional height above the socket to accommodate the attachment scheme. The additional height needs to be considered when designing the heat-sink approach.

7.3.4 Optical Budget

Optical specifications for front-panel pluggable modules are typically defined at TP2 and TP3 as shown in Figure 12. The third option, “CPO Pigtail + jumper”, shows the inclusion of a mid-board optical connector which increases the overall optical budget. Mid-board optical connectors enable the use of only one pigtail length for each CPO module. They also can minimize damage from handling of the CPO pigtail and if needed facilitates rework of failing optical connectors and components.

On the transmit side, the additional loss can be remedied by increasing the transmit power, likely by increasing the laser power to meet the specifications at TP2. On the receive side, the additional loss is likely compensated for by requiring better received sensitivity either by an improved receiver or by reduced sensitivity margin in the receiver.

Given the impact of faceplate connector loss on the optical loss budget, it is essential to control the insertion loss of the connectors. A 51.2T switch will have 256-1024 fibers on the front panel. Standards compliant connectors may have a loss distribution with a "long tail" that will be present when utilizing many connectors. CPO switch integrators should use front panel optical connectors with better loss performance characteristics than standards. In the industry these connectors are often called "Ultra Low Loss" connectors and have maximum loss values of 0.35 dB for single mode and 0.2 dB for multimode at beginning of life.

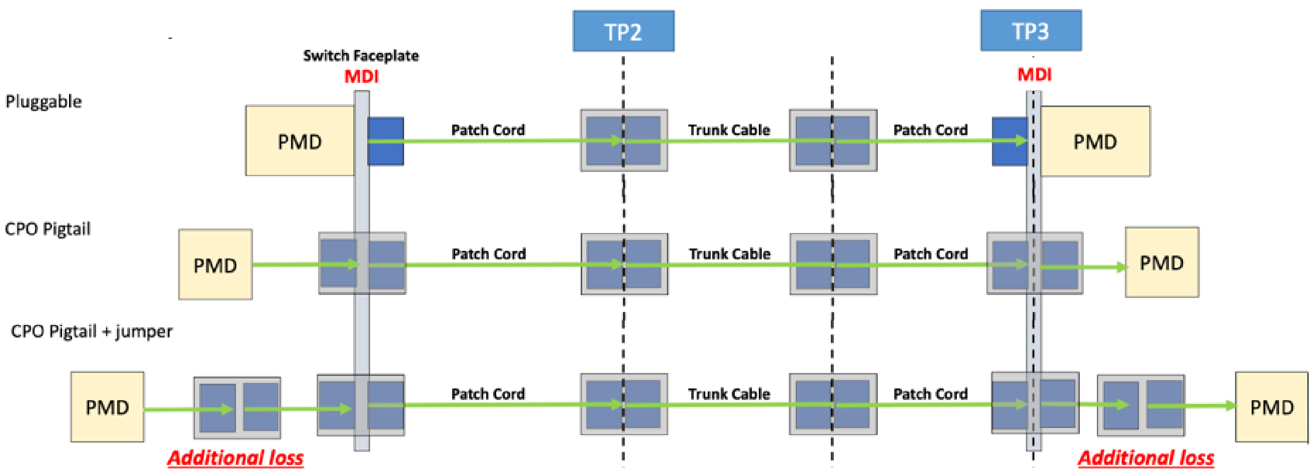


Figure 12: Impact of mid-board optical connectors.

Another key characteristic of the mid-board connector is that it is behind the front-panel such that it is likely mated and then not tested until the entire assembly is completed and ready for test. As a result, this "single-mate" scenario will likely require additional loss allocation compared to a typical optical connector for which there is easy access to clean and remate the connector if the insertion loss is high.

Dense optical systems will be built with components different than what is used in conventional front-panel pluggables. These dense optical technologies often have increased loss compared with conventional approaches. In addition, end-users often require interoperability with existing infrastructure employing conventional technologies. The combination of these two factors provides a significant challenge for dense optical engines.

However, in the case where interoperability is not required (book-ended applications), the optical budget can be optimized around the dense optical engine technology.

7.4 Thermal

7.4.1 Cooling Systems for Co-Packaging

Co-packaged engines will require some sort of thermal management, either a conduction path to remove heat or to isolate the engine from other heat-generating components. In either case, the thermal management approach will have to be compatible with the overall system cooling implementation. Figure 13 shows a typical 1RU, data center switch in use today. The aggregate bandwidth is 12.8Tb/s and contains 32 pluggable optical transceiver ports. These switches are typically cooled by fans that pull air in over the front-panel and exhaust through the rear.

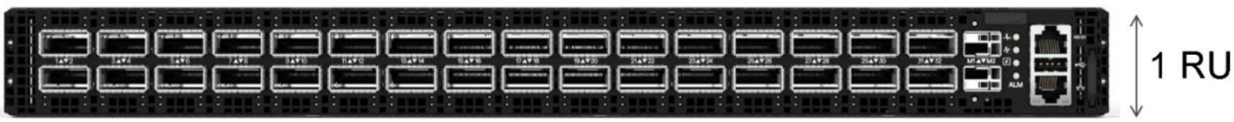


Figure 13: A typical 1RU data center Ethernet switch with 32 QSFP-DD 400Gb/s ports.

Table 5 shows typical power dissipation values for some of the key functional blocks.

Table 5: Typical 1RU data center switch power consumption*

12.8 Tb/s NPU power consumption:	432 W
32 400G QSFP56-DD ports @ 12 W each	384 W
Typical power consumption *(including fans, power suppliers, and typical power dissipation optics)*	900W
Total power consumption *(worst case, maximum traffic, highest ambient temp & fan speed)*	1500 W
Ambient Operating temperature	0 to + 45 ^{o}C
Redundant, hot swappable fans	7

** Operates with forward and reverse air flow*

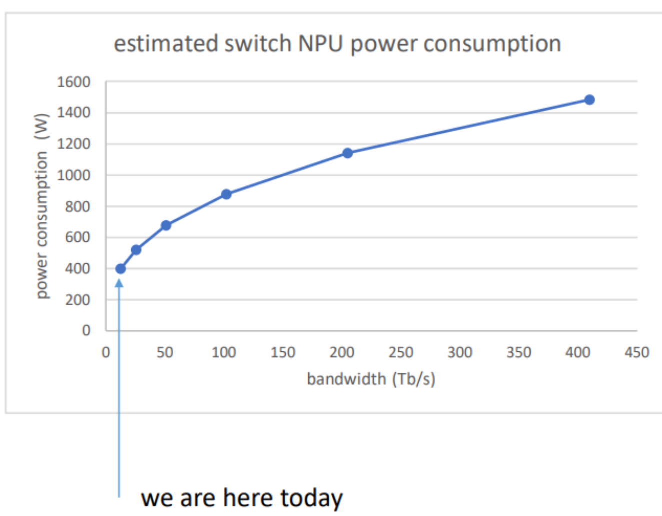


Figure 14: Switch ASIC power consumption trends.

In the near future, as network switching bandwidth increases, power consumption will increase (Figure 14) and forced air cooling approaches may be insufficient. Future network switches will likely require alternative system cooling implementations. A comparison of the different system cooling approaches is described in Table 6.

Table 6: Possible system cooling approaches.

Cooling Approach	Pros	Cons
Air-Cooled	Well-known, well understood technology	Limited cooling efficiency
	high reliability with multiple hot-swappable fan arrays	Acoustics (noise)
	widely used in data centers	
	low-cost	
Liquid Cooling -- Closed loop	Improved cooling capacity compared to air-cooling	limited (?) data-center deployments
	quieter than all-air cooling	Reliability mechanical pump)
	No external plumbing needed	more costly than air-cooling
Liquid Cooling -- Open loop	Improved cooling capacity compared to closed loop liquid cooling	Not widely deployed in data centers
	reliability local) is higher than closed loop cooling -- no pump	requires external source of flowing liquid and heat exchanger
		Reliability--failure of external source can take down many units
		Costs (heat exchange module, chilled liquid network facility)
Immersive Cooling	Improved cooling capacity compared to open/closed loop liquid cooling	Not widely deployed in data centers (requires external source of flowing liquid and heat exchanger
	Potentially highest equipment density	Reliability (fluid contamination, pump system)
		Optics and fiber connectors need to be hermetic
		Requires major re-architecting of equipment
		Costs-- not deployed in volume

7.4.2 Reported Thermal Data:

Component temperatures or thermal margins are required by component and system designers as well as operators to assess operational status. Typically, the laser case/base temperature is monitored for this purpose as it reflects the status of the laser's internal temperature control system. Co-packaged Optical systems integrate lasers systems with signal processing ASICS, and other photonics elements. These elements can have variable heat dissipation depending on operating mode, and FEC requirements. These power changes mean the temperature difference between the case and junction will vary for the same physical design. Consequently, a single case temperature may not be sufficient for monitoring system purposes as other devices approach operating limits with only a small variation in case temperature.

Although local case temperatures can reflect changes in overall internal power dissipation, the operational status of DSP's, drivers etc. will be better represented by the junction temperature sensors of these devices. It is recommended that the CPO reports laser case/base temperature and identifies its monitor location in addition to reporting at least one other temperature or thermal margin value that reflects the junction temperature of any DSP or other photonics element.

7.5 Power

As seen in Table 1, the estimated energy efficiency for co-packaged dense optical engines is expected to range from 5pJ/bit to 15pJ/bit depending on the particular application and CPO generation. For example, a 3.2T optical engine with a 10pJ/bit energy efficiency will consume 32W. A 3.2T optical engine footprint may be on the order of 20x20 mm^2. Such a large power in a small area result in a power density of 8W/cm^2 which is much higher than what the optical industry is accustomed to.

7.5.1 Supply Voltages, Currents

Different implementations will be architected employing differing technologies and different IC nodes resulting a variety of supply voltages and current draws for the supplies. For instance, an engine may include an advanced CMOS ASIC and a microcontroller (µC) which typically have supply voltages well below 1.0 volt. The engine may also need a supply to drive the high-speed I/O and perhaps higher voltages for some of the optical components.

It is assumed the power supply conversion will be external to the engine as the power supply components will probably add to the engine size and height. Therefore, the host will need to supply the CPA with the necessary power supplies.

Even if the industry agrees to a common set of supplies, the required current draw per supply will vary depending on the implementation.

The number of supplies and the max current draw will drive the number of power related contacts for the engine as the current/contact guidelines are considered for the socket.

7.6 Management Interface

7.6.1 CMIS Over 2-Wire, SPI

Typically, pluggable modules serve one or two ports, however, dense optical engines will serve many more ports. As an example, I2C was specified as a 2-wire management interface in the CMIS by the QSFP-DD MSA. In a high-density co-packaging application, the same MIS interface will need to serve many more ports. Switching to a faster MIS I/F such as SPI would improve the time for servicing the engines.

7.7 Environmental

The applications discussed in Section 6 are typically found in indoor, data center environments as opposed to outdoor environments. Operating temperature ranges are typically in the range of room temperature or higher than room temperatures and in next generation, much higher than room temperature due to the power dissipation of these high-performance systems. Some typical high-level operating conditions for a data center include the following:

- Altitude: 0 – 1800 meters (could include derating provisions)
- Relative Humidity (RH): 90 % max
- Ambient Temperature: 15 – 35 C

For co-packaging implementations more in-depth discussion and analysis will be needed to determine the operating case temperatures or internal temperatures and which kind of thermal management solution is employed (see Section 7.4.1).

7.8 Reliability, Redundancy and Repairability

The use of co-packaged engines is by nature less field serviceable than front panel pluggable designs. As a result, there is a need for a reliability framework at both component and system level to align with the target application requirements. For data center switch network fabrics, redundant links are utilized to achieve acceptable performance even under fault conditions. Applications involving AI and Machine Learning are typically less tolerant of a link failure due to higher aggregate bandwidth requirements and a greater level of connectivity for acceptable cluster performance.

A generic reliability curve is shown in Figure 15. The goal is to establish solid fabrication, processing, and assembly approaches with effective defect screens to minimize infant mortality. Component failure rates must be established that are compatible and consistent with system failure rate targets for *random failures.* In addition, it's expected that adequate instrumentation and monitoring functions will be implemented to enable *pre-emptive service or replacement* due to wear-out.

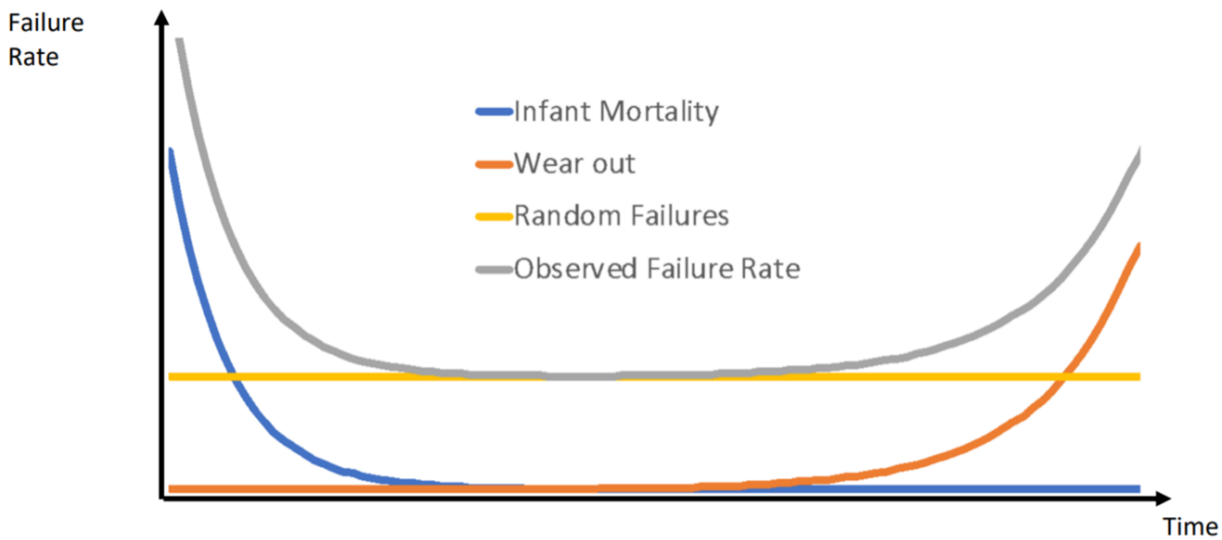


Figure 15: Generic reliability curve for co-packaging applications.

7.8.1 Infant Mortality Targets and Over-Life Targets

Current pluggable transceiver module failure rates (~ 300 FIT) are insufficient if simply scaled for CPO applications. End system reliability must be achieved by leveraging integration. Table 7 shows the reliability targets for a data center network switch having an aggregate bandwidth of 51.2Tb/s implemented with sixteen 3.2Tb/s co-packaged engines.

Table 7: Reliability targets.

	N	AFR[5]	MTBF[5] (hours)	FIT	Service Life (years)
CPO Engine[6]	16	0.01%	100M	10	6
3.2Tb/s Laser Source[7]	16	0.04%	20M	50	6
Rest of System	1 (Sum)	0.09%	10M	100	6
Total System		**<1%**		**<1146**	**6**

Further study is required to confirm the reliability of CPO implementations. Redundancy at component or sub-system level may be required to achieve overall system reliability targets. Furthermore, some implementations with reduced data-throughput performance, e.g., lane reduction of multi-lane interconnects, maybe required to enhance overall system availability.

[5] AFR = Annualized Failure Rate (% per year), MTBF=Mean-Time-Between-Failures
[6] Contribution to reliability from an engine excluding contribution from lasers
[7] Contribution to reliability from lasers excluding contribution from engine.

8 Summary

This Framework Document has addressed some of the key application spaces and relevant technology considerations for co-packaging of optical and electrical communication interfaces with one or more ASICs. Several optical and electrical interfaces as well as mechanical & thermal approaches have been presented which could benefit from a standardization process, e.g., an Implementation Agreement in the OIF. There are still other technology details and implementation aspects missing from this document that will warrant further study and may lead to additional standardization efforts.

9 References

9.1 Informative References

- IEEE Standard for Ethernet--Amendment 10: Media Access Control Parameters, Physical Layers, and Management Parameters for 200 Gb/s and 400 Gb/s Operation
- IEEE Standard for Ethernet--Amendment 11: Physical Layers and Management Parameters for 100 Gb/s and 400 Gb/s Operation over Single-Mode Fiber at 100 Gb/s per Wavelength
- IEEE 802.3ck (in-process)
- CEI-112G-XSR-PAM4 (in-process)
- IEC 60825-1: 2014 Safety of laser products – Part 1: Equipment classification and requirements
- IEC 60825-2: 2021 Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)

10 Appendix A: Glossary

AGC: Automatic gain control. Refers to the adjustment of the gain to enhance the dynamic range of the amplifier.

AI: Artificial Intelligence.

AIB: Advanced Interface Bus. A chip-to-chip communications interface.

ASIC: Application specific integrated circuit.

CCA: Copper Cable Assembly

CDR: Clock and data recovery.

CMIS: Common Management Interface Specification. Refers to an industry specification which implements I2C, two-wire serial interface for monitoring and control of various elements of co-packaging.

CMOS: Complimentary Metal-Oxide-Semiconductor. A common silicon ASIC fabrication process.

Co-Packaged Assembly Socket: A co-packaged assembly attached to the host board with a removable interface.

Co-Packaged Assembly Substrate: The substrate containing the ASIC and co-packaged engine.

CPA: Co-Packaged Assembly**.** ASIC plus engine (optical or electrical)

CPO: Co-Packaged Optics**.** Active optical components attached to a common substrate containing ASICs.

CTLE: Continuous time linear equalizer. Sometimes this is referred to as a “peaking” circuit where the rising or falling edges have overshoot.

CXL: Compute Express Link is an open industry standard interconnect offering high-bandwidth, low latency connectivity between host processor and devices such as accelerators, memory buffers, and smart I/O devices.

DSP: Digital Signal Processor.

EIC: Electrical Integrated Circuit. Refers to the electrical portion of an optical engine---may contain driver electronics to drive a laser or optical modulator as well as a transimpedance amplifier and post amplifier to convert a photo-current (arising from the photodetector) into a usable electrical signal.

ELS: External Light Source. A high-power cw optical laser source providing light for the modulator portions of an optical engine. It is located outside the boundary of the optical engine and therefore is likely to experience a different set of environmental conditions.

FEC: Forward Error Correction.

FIT: Failures in Time (1e9 hours).

Front Panel (Faceplate): The user accessible boundary of the system which in this document refers to the panel of a “19-inch rack”.

I/O: Input/Output driver. The output driver on the switch or processor host ASIC.

IA: Implementation Agreements, OIF documents that specify various names their defined interface specifications.

Integrated Light Source: A high-power cw optical laser source providing light for the modulator portions of an optical engine. It is bonded to the optical engine and typically launches light into the photonic engine waveguides via evanescent coupling.

LD-DRV: Laser diode driver. Refers to the ASIC which drives the laser or more generally, the optoelectronic device, which effectively acts as an electrical-to-optical converter.

MCM: Multi-Chip Module.

MMF: Multi-Mode Fiber. Optical fiber that transmits multiple spatial modes. Core diameters are much larger than the wavelength of the light being transmitted, e.g., 50 µm.

MPO: Multiple-fiber Push-On/Pull-off. An optical fiber connector that can support multiple fiber connections.

MR: Medium reach. Refers to the on-going project in OIF, CEI-112G-MR-PAM4, which is an electrical interface specification for package substrate distances of approximately 500mm, or 20 dB channel loss at the Nyquist frequency of the baud rate.

NIC: Network Interface Card.

NPU: Network Processing Unit. For example, a data center switch contained in a 1 RU chassis.

NRZ: Non return to zero, a binary code in which 1s are represented by one significant condition (usually a positive voltage or presence of light) and 0s are represented by some other significant condition (usually a negative voltage or absence of light), with no other neutral or rest condition.

OIC/PIC: Optical Integrate Circuit/Photonic Integrated Circuit. Typically refers to the optical portion of an optical engine---may contain waveguides, splitters, combiners, modulators as well as photodetectors.

On-chip Light Source: A high-power cw optical laser source providing light for the modulator portions of an optical engine. It is attached to the optical engine and typically uses an imaging element (e.g., lens, turning mirror) to couple light into the optical waveguides of the optical engine. Since the light source is on-chip, the temperature range of operation is similar to that experienced by the photonic engine.

Optical Chiplet (Optical Engine (OE), Optical Tile, CPO Module): The active optical element converting electrical signals from an ASIC to optical ones and vice-a-versa.

Optical/Electrical Engine (EE) Socket: An optical or electrical engine attached to the co-packaged assembly substrate with a removable interface.

Optical/Electrical Engine Substrate: The substrate on which the optical or electrical engine is attached to.

PAMx: Pulse-amplitude modulation is a form of signal modulation where the message information is encoded in the amplitude of a series of signal pulses. For optical links it refers to intensity modulation. As an example, PAM4 is a two-bit modulation that will take two bits at a time and map the signal amplitude to one of four possible levels.

PCIe: Peripheral Component Interconnect Express.

PIC: Photonic Integrated Circuit.

Pluggable Optics: Optical transceivers that are inserted into the front-panel of a system rack and provide the end-user with a variety of connection types. Some example form-factors include SFP, QSFP, QSFP-DD, and OSFP)

PSMx: Parallel Single-Mode. An optical interface specification that uses “x” parallel single mode fibers to transmit/receive optical signals. PSM4 is the terminology used to describe a 100Gb/s link using 4 pairs of single mode fibers with 25Gb/s per fiber.

QSFP-DD: Quad-Small Form-Factor Pluggable Double-Density. A transceiver form-factor with 8 electrical interface lanes in both directions capable of supporting up to 56Gb/s data rates per lane, for an aggregate data-rate of 400Gb/s in either direction.

RDL: Redistribution Layer.

ROSA: Receiver Optical Sub-Assembly. Refers to the photodetector and frequently the transimpedance amplifier within a package which usually provides a mechanism to align and couple the optical signal contained in the incoming fiber to the photodetector.

RU: Rack Unit. A unit of measure frequently used as a measurement of the overall height of 19-inch rack frames, as well as the height of equipment that mounts in these frames. The height of the frame or equipment is expressed as multiples of rack units, e.g., 1RU, 2RU, 3RU, etc.

SerDes: Serializer/Deserializer.

SPI: Serial Peripheral Interface.

TIA: Transimpedance amplifier. A photodetector is connected to this electronic device which converts the photo-current from the photodetector into a voltage.

TOSA: Transmitter Optical Sub-Assembly. Refers to the laser and package which usually provides a mechanism to align and couple the output of the laser to an optical fiber.

TPx: Test Points, TP2, TP3 as defined in IEEE.

VCSEL: Vertical Cavity Surface Emitting Laser. A type of laser, which for optical communications applications, uses wavelengths in the range of 850 nm with multi-mode optical fibers.

WDM: Wavelength Division Multiplexing. An optical communications technology which combines (multiplexes) several optical carrier signals of different wavelengths onto a single optical fiber.

XSR: Extra short reach. Refers to an on-going project in the OIF, CEI-112G-XSR-PAM4, which is an electrical interface specification for package substrate distances of approximately 50mm, or 10 dB channel loss at the Nyquist frequency of the baud rate.

11 Appendix B: Generalized Laser Safety for MPO-Based ELS Modules

11.1 Introduction

This appendix explains the requirements for laser product classification, laser hazard levels, according to the IEC standards IEC60825-1 and IEC60825-2. For ELS modules covered by this framework document, those that have accessible MPO connectors, i.e., scenarios 2b and 3 in Figure 9, are analyzed in the following subsections. Calculations are provided for several foreseeable configurations of fibers in MPO connectors carrying various proposed power levels per fiber and at wavelengths suitable for -FR4 and/or -DR4 interfaces.

11.2 Laser Product Classification and Required Safety Features

Table 8: Laser product classification and required safety features for IEC/EN 60825-1 3rd edition.

Laser Class (IEC/EN 60825-1 3rd Ed)	FDA Class	Hazard Description
1	Class I	Safe under reasonably foreseeable conditions
1M	No equivalent	As for Class 1 except may be hazardous if user employs optics
1C	No equivalent	See documentation
2	Class II	Low power; eye protection normally afforded by aversion & active responses
2M	No equivalent	As for Class 2 except may be more hazardous if user employs optics
3R	Class IIIa	Direct intrabeam viewing may be hazardous
3B	Class IIIb	Direct intrabeam viewing normally hazardous
4	Class IV	High power; diffuse reflections may be hazardous

Per ANSI:

"…In any case there shall be a designated LSO for all circumstances of operation, maintenance, and service of a Class 3B or Class 4 laser or laser system…"

Table 9: Requirements Summary

Requirements subclause	Classification						
	Class 1*	Class 1M	Class 2	Class 2M	Class 3R	Class 3B	Class 4
Description of hazard class Annex C	Safe under reasonably foreseeable conditions	As for Class 1 except may be hazardous if user employs optics	Low power; eye protection normally afforded by aversion & active responses	As for Class 2 except may be more hazardous if user employs optics	Direct intrabeam viewing may be hazardous	Direct intrabeam viewing normally hazardous	High power; diffuse reflections may be hazardous
Protective housing 6.2	Required for each laser product; limits access necessary for performance of functions of the products						
Safety interlock in protective housing 6.3	Designed to prevent removal of the panel until accessible emission values are below that for Class 3R				Designed to prevent removal of the panel until accessible emission values are below that for Class 3B or 3R for some products		
Remote Interlock 6.4	Not required					Permits easy addition of external interlock in laser installation. Not required for some products in Class 3B	
Manual Reset 6.5	Not required						Requires manual reset if power interrupted or remote interlock is actuated
Key control 6.6	Not required					Laser inoperative when key is removed	
Emission warning device 6.7	Not required				Gives audible or visible warning when laser is switched on or if capacitor bank of pulsed laser is being charged. For Class 3R, only applies if invisible radiation is emitted		
Attenuator 6.8	Not required					Gives means to temporarily block beam	
Control locations 6.9	Not required				Controls so located that there is no danger of exposure to AEL above Classes 1 or 2 when adjustments are made		
Viewing optics 6.10	Not required		Emission from all viewing systems shall be below Class 1M AEL				
Scanning 6.11	Scan failure shall not cause product to exceed its classification						
Class label 7.2 to 7.7	Required wording		Figures 3 and 4 and required wording				
Aperture label 7.8	Not required				Specified wording required		
Radiation output label 7.9	Not required	Required wording					
Standards information label 7.9	Required on product or in information to user		Required wording				
Service access label 7.10.1	Not required	Required as appropriate to the class of accessible radiation					
Override interlock label 7.10.2	Required under certain conditions as appropriate to the class of laser used						
Wavelength range label 7.10 and 7.12	Required for certain wavelength ranges						
Burn hazard label 7.13	Required wording when AE at closest point of human access (3.5mm aperture) exceeds AEL of Class 3B					Not applicable	
User information 8.1	Operation manuals shall contain instructions for safe use. Additional requirements apply for Class 1M and Class 2M						
Purchasing and service information 8.2	Promotion brochures shall specify product classification; service manuals shall contain safety information						
Medical products 9.2	Not required					For the safety of medical laser products, IEC 60601-2-22 may be applied.	

*NOTE This table is intended to provide a convenient summary of requirements. See text of this standard for complete requirements. Due to the specific concept of Class 1C, the requirements for Class 1C laser products are not included in this table; in this Part 1, mostly generic requirements are specified; product type specific requirements are defined in vertical standards.

11.3 Laser Class (IEC 60825-1) Versus Laser Hazard Levels (IEC 60825-2)

The laser eye safety levels for IEC 60825-1 (Table 1) and for IEC 60825-2 (Table 10) are *different*.

Table 10: Summary of requirements for location types in OFCS (IEC 60825-2: 2021)

Hazard level	Location type		
	Unrestricted	Restricted	Controlled
1	No requirements	No requirements	No requirements
1M	Hazard level 1 for output power from connectors that can be opened by an end-user [a] No labelling or marking required [b]	No labelling or marking required if output power from connectors that can be opened by end-user are hazard level 1. If output is hazard level 1M then labelling or marking is required [b]	No requirements
2	Labelling or marking [b]	Labelling or marking [b]	Labelling or marking [b]
2M	Labelling or marking [b], and hazard level 2 from connector [a]	Labelling or marking [b]	Labelling or marking [b]
3R	Not permitted [c]	Labelling or marking [b], and hazard level 1M or 2M from connector [a]	Labelling or marking [b], and hazard level 1M or 2M from connector [a]
3B	Not permitted [c]	Not permitted [c]	Labelling or marking [b], and hazard level 1M or 2M from connector [a]
4	Not permitted [c]	Not permitted [c]	Not permitted [c]

[a] See 4.4.

[b] See 4.5.

[c] Where systems employ normal transmitting power levels exceeding the acceptable hazard level for the particular location type (see 4.9), protection systems such as automatic power reduction may be used to determine the actual hazard level. See 4.7.2 and 4.8.

11.3.1 Measurement Geometry

Table 11: Measurement aperture diameters and measurement distances for the default (simplified) evaluation.

	Condition 1 Applied to collimated beam where e.g. telescope or binoculars may increase the hazard[a]		**Condition 2** Applicable to optical fiber communications systems, see IEC 60825-2	**Condition 3** Applied to determine irradiation relevant for the unaided eye, for low power magnifiers and scanning beams	
Wavelength (nm)	**Aperture Stop (mm)**	**Distance (mm)**		**Aperture Stop / Limiting aperture (mm)**	**Distance (mm)**
< 302.5	-	-		1	0
≥ 302.5 to 400	7	2,000		1	100
≥ 400 to 1,400	50	2,000	See Note 1 under 5.4.1	7	100
≥ 1,400 to 4,000	7 x Condition 3	2,000	See Note 1 under 5.4.1	1 for $t \leq 0.35$ s $1.5\ t^{3/8}$ for $0.35\text{s} < t < 10$ s 3.5 for $t \geq 10$ s	100
≥ 4,000 to 10^5	-	-		1 for $t \leq 0.35$ s $1.5\ t^{3/8}$ for $0.35\text{s} < t < 10$ s 3.5 for $t \geq 10$ s	0
≥ 10^5 to 10^6	-	-		11	0
NOTE: The descriptions below the "Condition" headings are typical cases for information only and not intended to be exclusive.					
[a] Condition 1 is not applied for classification of laser products intended for use exclusively indoors and where intrabeam with telescopic optics such as binocular telescopes is not reasonably foreseeable.					

Two measurement conditions are specified for the determination of the accessible emission. Condition 1 is applied for wavelengths where aided viewing of collimated beams with telescopic optics may increase the hazard. Condition 3 applies to the unaided eye. For power and energy measurement of scanned laser radiation, only Condition 3 shall be used. For classification of laser products intended for use exclusively indoors and where intra-beam viewing with telescopic optics such as binoculars is not reasonably foreseeable, it is not required to apply Condition 1.

NOTE 1: Measurement Condition 3 also includes an evaluation of the radiation accessible for viewing with a low power magnifying glass. Viewing with higher power magnifying optics as might occur with fiber optic systems is covered in IEC 60825-2.

Limitations of the classification scheme are discussed in Clause C.3, suggesting cases where additional risk analysis and warnings might be appropriate. Condition 2 was used in previous editions of this Part 1 as the "magnifying glass" condition.

The most restrictive of the applicable measurement conditions shall be applied. If the most restrictive condition is not obvious, both conditions shall be evaluated. For Classes 1M or 2M, both conditions always need to be evaluated.

11.4 OFCS Power Limits (IEC 60825-2: 2021)

Table 12: OFCS power limits for 11 µm mode field diameter single-mode fiber and 0.1 numerical aperture multimode fibers (core diameter 50 µm).

Wavelength and Fiber Type	Hazard Level					
	1	1M	2	2M	3R	3B
633 nm (MM)	1.95 mW (+2.9 dBm)	3.77 mW (+5.8 dBm)	5.00 mW (+7.0 dBm)	9.66 mW (+9.9 dBm)	25.0 mW (+14.0 dBm)	500 mW (+27.0 dBm)
780 nm (MM)	2.82 mW (+4.5 dBm)	5.45 mW (+7.4 dBm)	-	-	14.5 mW (+11.6 dBm)	500 mW (+27.0 dBm)
850 nm (MM)	3.89 mW (+5.9 dBm)	7.52 mW (+8.8 dBm)	-	-	20.0 mW (+13.0 dBm)	500 mW (+27.0 dBm)
980 nm (MM)	7.08 mW (+8.5. dBm)	13.7 mW (+11.4 dBm)	-	-	36.3 mW (+15.6 dBm)	500 mW (+27.0 dBm)
980 nm (SM)	1.80 mW (+2.5 dBm)	2.66 mW (+4.2 dBm)	-	-	9.21 mW (+9.6 dBm)	500 mW (+27.0 dBm)
1270 nm (MM)	140 mW (+21.4 dBm)	270 mW (+24.3 dBm)	-	-	500 mW (+27.0 dBm)	500 mW (+27.0 dBm)
1270 nm (SM)	46.2 mW (+16.6 dBm)	76.5 mW (+18.8 dBm)	-	-	237 mW (+23.7 dBm)	500 mW (+27.0 dBm)
1310 nm (MM)	481 mW (+26.8 dBm)	500 mW (+27.0 dBm)	-	-	500 mW (+27.0 dBm)	500 mW (+27.0 dBm)
1310 nm (SM)	166 mW (+22.2 dBm)	277 mW (+24.4 dBm)	-	-	500 mW (+27.0 dBm)	500 mW (+27.0 dBm)
1400 nm to 1600 nm (MM)	13.3 mW (+11.2 dBm)	371 mW (+25.7 dBm)	-	-	See note to 3.9	500 mW (+27.0 dBm)
1420 nm (SM)	10.1 mW (+10.0 dBm)	115 mW (+20.6 dBm)	-	-	See note to 3.9	500 mW (+27.0 dBm)
1550 nm (SM)	10.2 mW (+10.1 dBm)	136 mW (+21.3 dBm)	-	-	See note to 3.9	500 mW (+27.0 dBm)
NOTE 1: Hazard levels 1M and 2M The maximum power shown in the table for 11 µm fiber is limited by the power density. The precise fiber power limit is therefore determined by the minimum expected beam divergence, which is in turn dependent on the MFD of a single-mode fiber. This can change for different values of the MFD and there are significant changes in Class limits as the MFD changes. Some connectors use enlarged MFD and the far field divergence is lower. These connectors can result in a higher hazard level and the higher hazard level is assigned when using these connectors.						
NOTE 2: Wavelength 1270 nm Wavelength 1270 nm corresponds to the shortest wavelength in the datacom applications, e.g., LAN-WDM.						
NOTE 3: Fiber parameters The fiber parameters used are the most conservative cases; single-mode figures are calculated for a fiber with an 11 µm MFD, and multimode figures for a fiber with a numerical aperture of 0.18. Many systems operating at 980 nm and 1550 nm use fibers with smaller MFDs. For example, the limit for hazard level 1M when a wavelength of 150 nm is transmitted along dispersion shifted fiber cables having upper limit values of MFD of 9.1 µm is 197 mW.						

The maximum mean power within the fiber for each hazard level for the most important wavelengths and optical fiber types used in OFCS is presented in Table 12. The values shown assume that APR is not in operation. For most typical systems with duty cycles between 10 % and 100 %, the peak power can be allowed to increase with duty cycle in an inversely proportional manner. However, for duty cycles ≤ 50 %, it is most straightforward to limit the peak powers to twice these mean power limits, although IEC 60825-1 can be used for a more sophisticated analysis to identify any increase in peak powers permissible for these types of systems. This is especially valid when "visible sources" with wavelengths in the photochemical hazard area are used.

For the most common single-mode fibers, the point source limits need to be applied while for graded index multimode fibers with a core diameter of 62.5 µm (GI 62.5), the effect of angular subtense, which is linked to *C*6, needs to be considered for wavelengths between 400 nm and 1 400 nm.

The following aperture diameter and measurement distances are to be used for Condition 2 measurements:

⇒ **3.5 mm at 35 mm for wavelengths ≥ 302.5 nm and < 1,400 nm.**

⇒ **3.5 mm at 14 mm for wavelengths ≥ 1,400 nm and < 4,000 nm.**

11.5 Accessible Emission Limit (AEL) Calculations, Wavelength (IEC 60825-1:2014 Laser Class 1/1M)

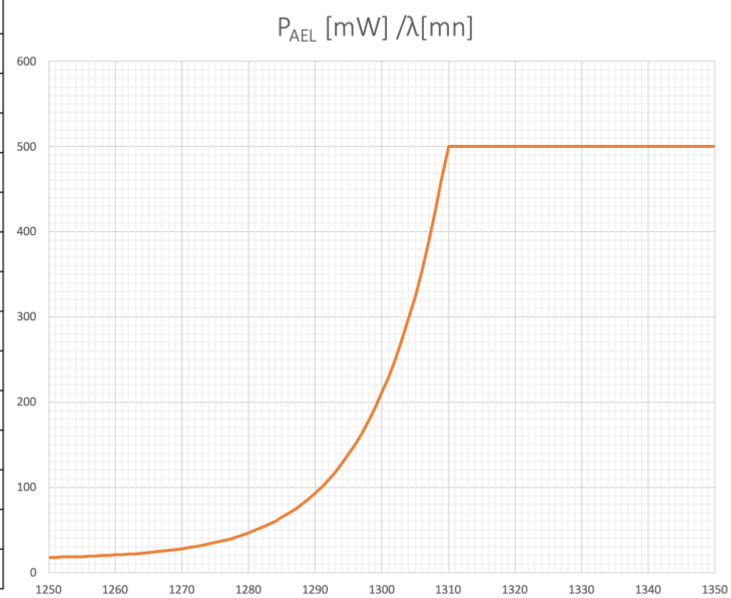
AEL Calculations
Wavelength [nm]: 1250-1350nm
Point Source (single fiber)

$\alpha \leq 1.5$ mrad: AEL = $3.9 * 10^{-4} C_4 C_7$ W

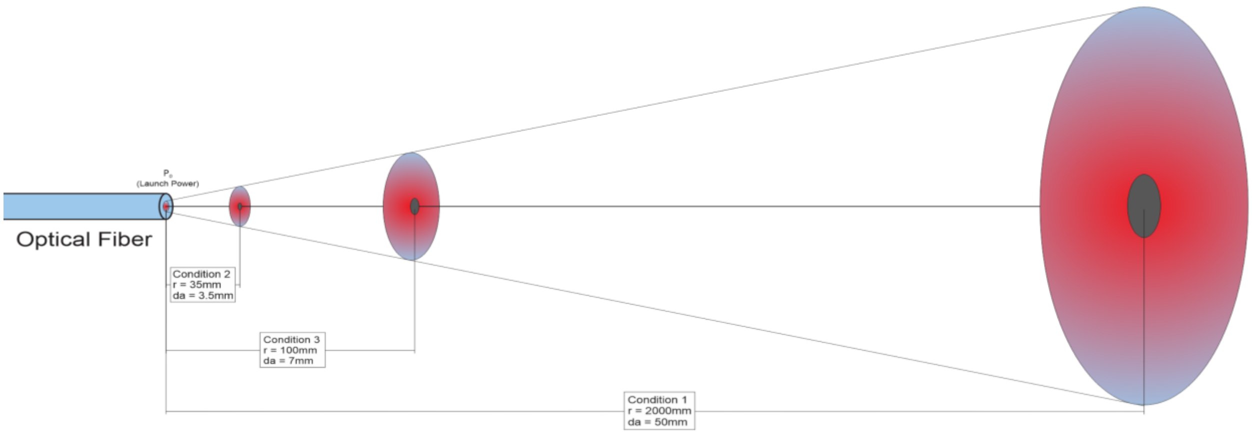
$C_4 = 5$
$C_7 = 8 + 10^{0.04(\lambda - 1\,250)}$
t = 100 s
P_0 based on Condition 3 (100 mm, 9.6 µm)

Wavelength [nm]	AEL [mW]	P_0 [mW]	P_0 [dBm]
1271	29.09	99.73	19.99
1291	100.72	345.30	25.38
1311	500.00	500.00	26.99
1331	500.00	500.00	26.99

Wavelength [nm}	AEL [mW]	P_0 [mW]	P_0 [dBm]
1250	17.6	60.2	17.8
1255	18.7	64.1	18.1
1260	20.5	70.3	18.5
1265	23.4	80.1	19.0
1270	27.9	95.7	19.8
1275	35.1	120.3	20.8
1280	46.5	159.4	22.0
1285	64.6	221.4	23.5
1290	93.2	319.6	25.0
1295	138.6	475.3	26.8
1300	210.6	500.0	27.0
1305	324.7	500.0	27.0
1310	500.0	500.0	27.0
1315	500.0	500.0	27.0
1320	500.0	500.0	27.0
1325	500.0	500.0	27.0
1330	500.0	500.0	27.0
1335	500.0	500.0	27.0
1340	500.0	500.0	27.0
1345	500.0	500.0	27.0
1350	500.0	500.0	27.0



11.6 Exposure Level Versus Fiber Launch Power P_0 At 1271 nm



$$P_a = \eta P_0 = \left[1 - e^{-\left(\frac{d_a}{d_{63}}\right)^2}\right] P_0$$

Where $\mathbf{d_{63}} = \dfrac{2\sqrt{2}r\lambda}{\pi\omega_0}$

Standard Single Mode Fiber SMF28e+

Wavelength [nm]	Mode Field Diameter (ω_0) [µm]
1310	9.2±0.4
1550	10.4±0.5

$P_{AEL} = 3.9 * 10^{-4} C_4 C_7$ W

$C_4 = 5$

$C_7 = 8 + 10^{0.04(\lambda - 1250)}$

t = 100s

$\omega_0 = 9.6\mu m$

$\lambda = 1271nm$

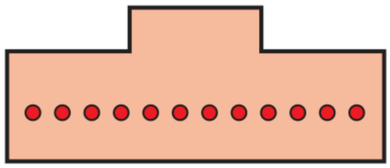
	Cond 1	Cond 2	Cond 3
r [mm]	2000	35	100
d_a [mm]	50.00	3.50	7.00
d_{63} [mm]	208.05	3.64	10.40
η	0.0561	0.603	0.364
η [dB]	-12.5104	-2.19683	-4.38899
P_{AEL} [W]	0.02909	0.02909	0.02909
P_0 [W]	0.5184	0.0482	0.0799
P_0 [dBm]	27.15	16.83	19.02

	Condition 1	Condition 2	Condition 3
Laser Class 1	N/A[1]	N/A[3]	X
Laser Class 1M	X[2]	N/A	X
Hazard Level 1	N/A[1]	X	X[2]
Hazard Level 1M	X[2]	N/A	X

[1] Condition 1 is not applied for classification of laser products intended for use exclusively indoors and where intrabeam viewing with telescopic optics such as binocular telescopes is not reasonably foreseeable.
[2] Condition is applied, but will not represent the worst case configuration for diverging beam
[3] Several test agencies are applying condition 2 to Laser Classification measurements to reduce confusion between Laser Class and Hazard Level

11.7 AEL Calculations for MPO Connector – Condition 3: Aperture Distance 100 mm

11.7.1 All Fibers Active



AEL Calculations

Point Source (single fiber)

α ≤ 1.5 mrad: AEL = $3.9 * 10^{-4}$ C_4 C_7 W

Extended Source (multiple fibers)

α > 1.5 mrad: AEL = $3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W

$C_4 = 5$

$C_7 = 8 + 10^{0.04(\lambda - 1\,250)}$

$C_6 = \alpha/\alpha_{min}$

$T_2 = 10 * 10^{[(\alpha - \alpha min)/98.5]}$ s

t = 100s

Wavelength [nm]: **1271 nm**

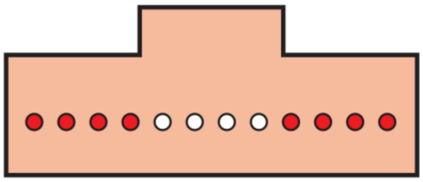
Fiber Spacing [µm]: **250 µm**

Fiber Diameter (MFD) [µm]: **9.6 µm**

Number of Fibers	angle of subtense vertical [mrad]	angle of subtense horizontal [mrad]	effective angle of subtence [mrad]	C4	C6	C7	T2[s]	AEL Formula	AEL [mW]	AEL per Channel [mW]
1	1.50	1.50	1.50	5.000	1.000	14.9	10.00	$3.9 * 10^{-4}$ C_4 C_7 W	29.091	29.091
2	1.50	2.60	2.05	5.000	1.365	14.9	10.13	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	39.961	**20.0**
3	1.50	5.10	3.30	5.000	2.199	14.9	10.43	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	63.882	21.3
4	1.50	7.60	4.55	5.000	3.032	14.9	10.74	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	87.453	21.9
5	1.50	10.10	5.80	5.000	3.865	14.9	11.06	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	110.676	22.1
6	1.50	12.60	7.05	5.000	4.698	14.9	11.38	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	133.555	22.3
7	1.50	15.09	8.30	5.000	5.532	14.9	11.72	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	156.094	22.3
8	1.50	17.59	9.55	5.000	6.365	14.9	12.07	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	178.297	22.3
9	1.50	20.09	10.80	5.000	7.198	14.9	12.43	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	200.166	22.2
10	1.50	22.59	12.05	5.000	8.031	14.9	12.80	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	221.705	22.2
11	1.50	25.09	13.30	5.000	8.864	14.9	13.17	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	242.918	22.1
12	1.50	27.59	14.54	5.000	9.696	14.9	13.57	$3.5 * 10^{-3}$ C_6 C_7 $T_2^{-0.25}$ W	263.808	22.0

For Laser Class 1/Hazard Level 1M evaluations of MPO connectors two neighboring emitters present the worst-case configuration.

11.7.2 Two Groups of 4 Fibers Active



AEL Calculations

Point Source (single fiber)

$\alpha \leq 1.5$ mrad: AEL = $3.9 * 10^{-4} C_4 C_7$ W

Extended Source (multiple fibers)

$\alpha > 1.5$ mrad: AEL = $3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W

$C_4 = 5$

$C_7 = 8 + 10^{0.04(\lambda - 1250)}$

$C_6 = \alpha/\alpha_{min}$

$T_2 = 10 * 10^{[(\alpha - \alpha min)/98.5]}$ s

t = 100s

Wavelength [nm]: **1271 nm**

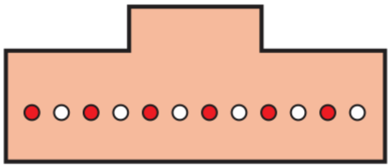
Fiber Spacing [µm]: **250 µm**

Fiber Diameter (MFD) [µm]: **9.6 µm**

Number of Fibers	angle of subtense vertical [mrad]	angle of subtense horizontal [mrad]	effective angle of subtence [mrad]	C4	C6	C7	T2[s]	AEL Formula	AEL [mW]	AEL per Channel [mW]
1	1.50	1.50	1.50	5.000	1.000	14.9	10.00	$3.9 * 10^{-4} C_4 C_7$ W	29.091	29.091
2	1.50	2.60	2.05	5.000	1.365	14.9	10.13	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	39.961	**20.0**
3	1.50	5.10	3.30	5.000	2.199	14.9	10.43	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	63.882	21.3
4	1.50	7.60	4.55	5.000	3.032	14.9	10.74	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	87.453	21.8
5	1.50	10.10	5.80	5.000	3.865	14.9	11.06	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	110.676	
6	1.50	12.60	7.05	5.000	4.698	14.9	11.38	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	133.555	
7	1.50	15.09	8.30	5.000	5.532	14.9	11.72	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	156.094	
8	1.50	17.59	9.55	5.000	6.365	14.9	12.07	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	178.297	
9	1.50	20.09	10.80	5.000	7.198	14.9	12.43	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	200.166	40.0
10	1.50	22.59	12.05	5.000	8.031	14.9	12.80	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	221.705	36.9
11	1.50	25.09	13.30	5.000	8.864	14.9	13.17	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	242.918	34.7
12	1.50	27.59	14.54	5.000	9.696	14.9	13.57	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	263.808	33.0

For Laser Class 1/Hazard Level 1M evaluations of MPO connectors two neighboring emitters present the worst-case configuration.

11.7.3 Every Second Fiber Active



AEL Calculations

Point Source (single fiber)

$\alpha \leq 1.5$ mrad: AEL = $3.9 * 10^{-4} C_4 C_7$ W

Extended Source (multiple fibers)

$\alpha > 1.5$ mrad: AEL = $3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W

$C_4 = 5$

$C_7 = 8 + 10^{0.04(\lambda - 1\,250)}$

$C_6 = \alpha/\alpha_{min}$

$T_2 = 10 * 10^{[(\alpha - \alpha min)/98.5]}$ s

t = 100s

Wavelength [nm]: **1271 nm**

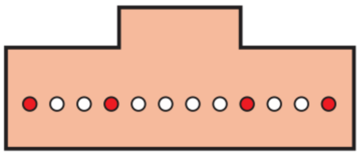
Fiber Spacing [µm]: **250 µm**

Fiber Diameter (MFD) [µm]: **9.6 µm**

Number of Fibers	angle of subtense vertical [mrad]	angle of subtense horizontal [mrad]	effective angle of subtence [mrad]	C4	C6	C7	T2[s]	AEL Formula	AEL [mW]	AEL per Channel [mW]
1	1.50	1.50	1.50	5.000	1.000	14.9	10.00	$3.9 * 10^{-4} C_4 C_7$ W	29.091	**29.091**
2	1.50	2.60	2.05	5.000	1.365	14.9	10.13	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	39.961	
3	1.50	5.10	3.30	5.000	2.199	14.9	10.43	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	63.882	31.9
4	1.50	7.60	4.55	5.000	3.032	14.9	10.74	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	87.453	
5	1.50	10.10	5.80	5.000	3.865	14.9	11.06	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	110.676	36.9
6	1.50	12.60	7.05	5.000	4.698	14.9	11.38	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	133.555	
7	1.50	15.09	8.30	5.000	5.532	14.9	11.72	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	156.094	39.0
8	1.50	17.59	9.55	5.000	6.365	14.9	12.07	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	178.297	
9	1.50	20.09	10.80	5.000	7.198	14.9	12.43	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	200.166	40.0
10	1.50	22.59	12.05	5.000	8.031	14.9	12.80	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	221.705	
11	1.50	25.09	13.30	5.000	8.864	14.9	13.17	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	242.918	40.5
12	1.50	27.59	14.54	5.000	9.696	14.9	13.57	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	263.808	

For Laser Class 1/Hazard Level 1M evaluations of MPO connectors with increased emitter spacing single emitters present the worst-case configuration.

11.7.4 Four Active Fibers with Maximum Separation



AEL Calculations

Point Source (single fiber)

$\alpha \leq 1.5$ mrad: AEL = $3.9 * 10^{-4}\, C_4\, C_7$ W

Extended Source (multiple fibers)

$\alpha > 1.5$ mrad: AEL = $3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W

$C_4 = 5$

$C_7 = 8 + 10^{0.04(\lambda - 1\,250)}$

$C_6 = \alpha/\alpha_{min}$

$T_2 = 10 * 10^{[(\alpha - \alpha min)/98.5]}$ s

t = 100s

Wavelength [nm]: **1271 nm**

Fiber Spacing [µm]: **250 µm**

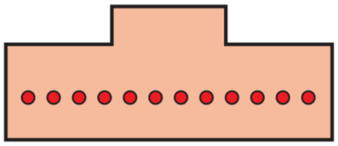
Fiber Diameter (MFD) [µm]: **9.6 µm**

Number of Fibers	angle of subtense vertical [mrad]	angle of subtense horizontal [mrad]	effective angle of subtence [mrad]	C4	C6	C7	T2[s]	AEL Formula	AEL [mW]	AEL per Channel [mW]
1	1.50	1.50	1.50	5.000	1.000	14.9	10.00	$3.9 * 10^{-4} C_4 C_7$ W	29.091	**29.091**
2	1.50	2.60	2.05	5.000	1.365	14.9	10.13	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	39.961	
3	1.50	5.10	3.30	5.000	2.199	14.9	10.43	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	63.882	
4	1.50	7.60	4.55	5.000	3.032	14.9	10.74	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	87.453	43.7
5	1.50	10.10	5.80	5.000	3.865	14.9	11.06	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	110.676	
6	1.50	12.60	7.05	5.000	4.698	14.9	11.38	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	133.555	
7	1.50	15.09	8.30	5.000	5.532	14.9	11.72	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	156.094	
8	1.50	17.59	9.55	5.000	6.365	14.9	12.07	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	178.297	
9	1.50	20.09	10.80	5.000	7.198	14.9	12.43	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	200.166	66.7
10	1.50	22.59	12.05	5.000	8.031	14.9	12.80	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	221.705	
11	1.50	25.09	13.30	5.000	8.864	14.9	13.17	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	242.918	
12	1.50	27.59	14.54	5.000	9.696	14.9	13.57	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	263.808	66.0

For Laser Class 1/Hazard Level 1M evaluations of MPO connectors with increased emitter spacing single emitters present the worst-case configuration.

11.8 AEL Calculations for MPO Connector – Condition 2: Aperture Distance 35 mm

11.8.1 All Fibers Active



AEL Calculations

Point Source (single fiber)

$\alpha \leq 1.5$ mrad: AEL = $3.9 * 10^{-4}\, C_4\, C_7$ W

Extended Source (multiple fibers)

$\alpha > 1.5$ mrad: AEL = $3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W

$C_4 = 5$

$C_7 = 8 + 10^{0.04(\lambda - 1\,250)}$

$C_6 = \alpha/\alpha_{min}$

$T_2 = 10 * 10^{[(\alpha - \alpha min)/98.5]}$ s

t = 100s

Wavelength [nm]: **1271 nm**

Fiber Spacing [µm]: **250 µm**

Fiber Diameter (MFD) [µm]: **9.6 µm**

Number of Fibers	angle of subtense vertical [mrad]	angle of subtense horizontal [mrad]	effective angle of subtence [mrad]	C4	C6	C7	T2[s]	AEL Formula	AEL [mW]	AEL per Channel
1	1.50	1.50	1.50	5.000	1.000	14.9	10.00	$3.9 * 10^{-4}\, C_4\, C_7$ W	29.091	**29.091**
2	1.50	7.42	4.46	5.000	2.972	14.9	10.72	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	85.778	42.9
3	1.50	14.56	8.03	5.000	5.353	14.9	11.65	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	151.291	50.4
4	1.50	21.70	11.60	5.000	7.733	14.9	12.66	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	214.048	53.5
5	1.50	28.84	15.17	5.000	10.113	14.9	13.76	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	274.130	54.8
6	1.50	35.97	18.74	5.000	12.491	14.9	14.96	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	331.618	55.3
7	1.50	43.10	22.30	5.000	14.868	14.9	16.26	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	386.589	55.2
8	1.50	50.23	25.87	5.000	17.244	14.9	17.68	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	439.120	54.9
9	1.50	57.35	29.43	5.000	19.618	14.9	19.21	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	489.286	54.4
10	1.50	64.47	32.99	5.000	21.990	14.9	20.88	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	500.000	50.0
11	1.50	71.58	36.54	5.000	24.360	14.9	22.68	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	500.000	45.5
12	1.50	78.68	40.09	5.000	26.728	14.9	24.65	$3.5 * 10^{-3}\, C_6\, C_7\, T_2^{-0.25}$ W	500.000	41.7

For Hazard Level 1 evaluations of MPO connectors single emitters present the worst-case configuration.

11.9 Burn Hazard Labeling

Warning for potential hazard to the skin or anterior parts of the eye

For Class 1, 1M, 2, 2M or Class 3R, if the accessible emission exceeds the AEL of Class 3B as determined with a 3,5 mm diameter aperture placed at the closest point of human access, an additional warning shall be given on a product label and in the information for the user (see 5.3 a) for Class 1 and 1M, see 5.3 c) for Class 2 and 2M, and see 5.3 d) for Class 3R).

The following warning shall be given on the product housing and in the information for the user. Text borders and symbols shall be black on a yellow background, including for Class 1.

LASER ENERGY - EXPOSURE NEAR APERTURE MAY CAUSE BURNS

NOTE The risk of skin injury is only likely for highly divergent beams for exposure close to the aperture.

While the placement of the explanatory label for Class 1 and 1M on the product is optional (see 7.2), the above warning is not optional.

11.10 AEL Calculations for Short Time Exposure (Laser class 1/1M)

AEL Calculations

Wavelength [nm]: 1271nm

Point Source (single fiber)

$\alpha \leq 1.5$ mrad: $E_{AEL} = 3.5 * 10^{-3}\ t^{0,75}\ C_7$ J

$C_7 = 8 + 10^{0.04(\lambda - 1\,250)}$

t = 10s - 0.1ms

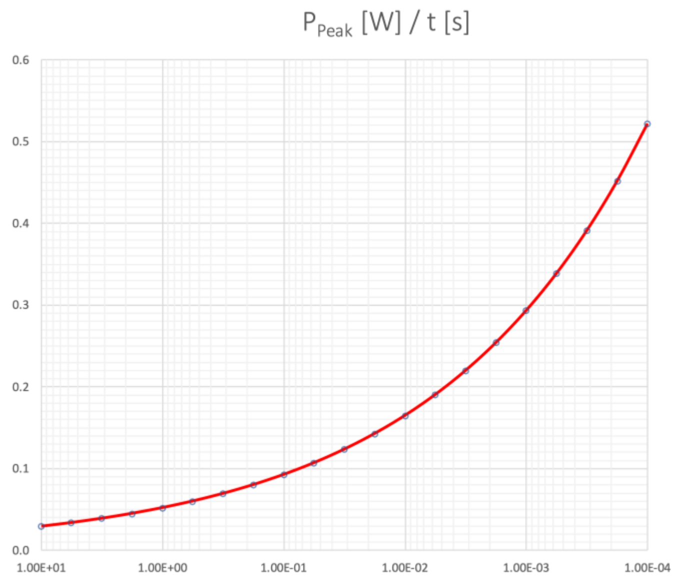
$P_{Peak} = E_{AEL}/t$

P_{0Peak} based on Condition 3 (100mm, 9.6µm)

Calculations a based on single pulse exposure as per IEC 60825-1

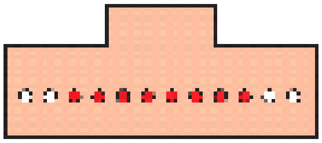
APR regulations as per IEC 60825-2 have not considered as the FDA/CDRH does not recognize IEC 60825-2 for FDA filings under laser notice #56.

t [s]	P_{peak} [W]	P_{0peak} [W]	P_{0peak} [dBm]
1.00E+01	0.029	0.101	20.0
5.62E+00	0.034	0.116	20.7
3.16E+00	0.039	0.134	21.3
1.78E+00	0.045	0.155	21.9
1.00E+00	0.052	0.179	22.5
5.62E-01	0.060	0.207	23.2
3.16E-01	0.070	0.239	23.8
1.78E-01	0.080	0.276	24.4
1.00E-01	0.093	0.318	25.0
5.62E-02	0.107	0.368	25.7
3.16E-02	0.124	0.424	26.3
1.78E-02	0.143	0.490	26.9
1.00E-02	0.165	0.566	27.5
5.62E-03	0.191	0.654	28.2
3.16E-03	0.220	0.755	28.8
1.78E-03	0.254	0.872	29.4
1.00E-03	0.294	1.007	30.0
5.62E-04	0.339	1.162	30.7
3.16E-04	0.392	1.342	31.3
1.78E-04	0.452	1.550	31.9
1.00E-04	0.522	1.790	32.5



11.11 Sample Scenarios for ELS Modules with Accessible MPO Connectors

11.11.1 Eight Fibers at 18 dBm Each (Wavelengths 1271 nm, 1291 nm, 1311 nm, 1331 nm)



1271nm represents the most restrictive wavelength

Number of Channels	angle of subtense vertical [mrad]	angle of subtense horizontal [mrad]	effective angle of subtense [mrad]	C4	C6	C7	T2[s]	AEL Formula	AEL [mW]	AEL per Channel
1	1.50	1.50	1.50	5.000	1.000	14.9	10.00	$3.9 * 10^{-4} C_4 C_7$ W	29.091	29.091
2	1.50	2.60	2.05	5.000	1.365	14.9	10.13	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	39.961	**20.0**
3	1.50	5.10	3.30	5.000	2.199	14.9	10.43	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	63.882	21.3
4	1.50	7.60	4.55	5.000	3.032	14.9	10.74	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	87.453	21.9
5	1.50	10.10	5.80	5.000	3.865	14.9	11.06	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	110.676	22.1
6	1.50	12.60	7.05	5.000	4.698	14.9	11.38	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	133.555	22.3
7	1.50	15.09	8.30	5.000	5.532	14.9	11.72	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	156.094	22.3
8	1.50	17.59	9.55	5.000	6.365	14.9	12.07	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	178.297	22.3

	Cond 1	Cond 2	Cond 3
r [mm]	2000	35	100
d_a [mm]	50	3.5	7
d_{63} [mm]	208.05	3.64	10.4
η	0.037	0.455	0.292
η [dB]	-12.51	-2.20	-4.39
P_{AEL} [mW] per Channel	20	20	20
P_0 [mW]	536.77	43.93	68.57
P_0 [dBm]	27.30	16.43	18.36

Hazard Level 1 Limit

Hazard Level 1M Limit
Laser Class 1 Limit

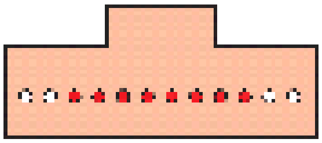
Hazard Level 1 emission levels are exceeded for continuous emission

Laser Class 1 & Hazard Level 1M emission limits are maintained for continuous emission

Hazard Level 1 emission limits are maintained if the exposure is limited to 2s or less.

Total Accessible Power > 500 mW => Burn Hazard Label required

11.11.2 Eight Fibers at 22 dBm Each (Wavelengths 1271 nm, 1291 nm, 1311 nm, 1331 nm)



1271nm represents the most restrictive wavelength

Number of Channels	angle of subtense vertical [mrad]	angle of subtense horizontal [mrad]	effective angle of subtense [mrad]	C4	C6	C7	T2[s]	AEL Formula	AEL [mW]	AEL per Channel
1	1.50	1.50	1.50	5.000	1.000	14.9	10.00	$3.9 * 10^{-4} C_4 C_7$ W	29.091	29.091
2	1.50	2.60	2.05	5.000	1.365	14.9	10.13	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	39.961	**20.0**
3	1.50	5.10	3.30	5.000	2.199	14.9	10.43	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	63.882	21.3
4	1.50	7.60	4.55	5.000	3.032	14.9	10.74	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	87.453	21.9
5	1.50	10.10	5.80	5.000	3.865	14.9	11.06	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	110.676	22.1
6	1.50	12.60	7.05	5.000	4.698	14.9	11.38	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	133.555	22.3
7	1.50	15.09	8.30	5.000	5.532	14.9	11.72	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	156.094	22.3
8	1.50	17.59	9.55	5.000	6.365	14.9	12.07	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	178.297	22.3

	Cond 1	Cond 2	Cond 3
r [mm]	2000	35	100
d_a [mm]	50	3.5	7
d_{63} [mm]	208.05	3.64	10.4
η	0.037	0.455	0.292
η [dB]	-12.51	-2.20	-4.39
P_{AEL} [mW] per Channel	20	20	20
P_0 [mW]	536.77	43.93	68.57
P_0 [dBm]	27.30	16.43	18.36

Hazard Level 1 Limit

Hazard Level 1M Limit
Laser Class 1 Limit

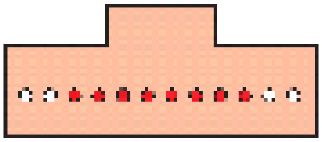
Hazard Level 1/1M and laser class 1 emission levels are exceeded for continuous emission

Emissions are within limits for Laser Class 1 & Hazard Level 1M if the exposure is limited to 0.3s or less.

Emissions are within limits for Hazard Level 1 if the exposure is limited to 50ms or less.

Total Accessible Power > 500 mW => Burn Hazard Label required

11.11.3 Four Fibers at 24 dBm Each (Wavelength 1311 nm Only)



Number of Channels	angle of subtense vertical [mrad]	angle of subtense horizontal [mrad]	effective angle of subtense [mrad]	C4	C6	C7	T2[s]	AEL Formula	AEL [mW]	AEL per Channel
1	1.50	1.50	1.50	5.000	1.000	283.4	10.00	$3.9 * 10^{-4} C_4 C_7$ W	500.000	500.0
2	1.50	2.60	2.05	5.000	1.365	283.4	10.13	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	500.000	250.0
3	1.50	5.10	3.30	5.000	2.199	283.4	10.43	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	500.000	166.7
4	1.50	7.60	4.55	5.000	3.032	283.4	10.74	$3.5 * 10^{-3} C_6 C_7 T_2^{-0.25}$ W	500.000	125.0

	Cond 1	Cond 2	Cond 3
r [mm]	2000	35	100
d_a [mm]	50	3.5	7
d_{63} [mm]	208.05	3.64	10.4
η	0.037	0.455	0.292
η [dB]	-12.51	-2.20	-4.39
P_{AEL} [mW] per Channel	125	125	125
P_0 [mW]	3354.82	274.54	428.54
P_0 [dBm]	35.26	24.39	26.32

Hazard Level 1 Limit

Hazard Level 1M Limit
Laser Class 1 Limit

Laser Class 1 & Hazard Level 1/1M emission limits are maintained for continuous emission

Total Accessible Power > 500 mW => Burn Hazard Label required

12 Appendix C: List of companies belonging to OIF when document is approved

Accton Technology Corporation	Hisense Broadband Multimedia Technologies Co., LTD	NVIDIA Corporation
ADVA Optical Networking	Huawei Technologies Co., Ltd.	O-Net Communications (Shenzhen) Limited
Advanced Fiber Resources (AFR)	I-Pex	Open Silicon Inc.
Alibaba	IBM Corporation	Optomind Inc.
Alphawave IP Inc.	Idea Sistemas Electronicos S.A.	Orange
Amphenol Corp.	II-VI Incorporated	PETRA
AnalogX Inc.	Infinera	Pointwo Technology
Applied Optoelectronics, Inc.	InnoLight Technology Limited	Precise-ITC, Inc.
Ayar Labs	Innolume GmbH	Quintessent Inc.
Banias Labs	Innovium	Ragile Networks, Inc.
BitifEye Digital Test Solutions GmbH	Integrated Device Technology	Rambus Inc.
Broadcom Inc.	Intel	Ranovus
Cadence Design Systems	IPG Photonics Corporation	Retym
China Telecom	Juniper Networks	Rockley Photonics
CICT	Kandou Bus	Rosenberger Hochfrequenztechnik GmbH & Co. KG
Ciena Corporation	KDDI Research, Inc.	Samsung Electronics Co. Ltd.
Cisco Systems	Keysight Technologies, Inc.	Samtec Inc.
Commscope Connectivity Belgium BVBA	Kuaishou Technology	Semtech Canada Corporation
Cornelis Networks, Inc.	Lumentum	Senko Advanced Components
Corning	Luxshare-ICT	Sicoya GmbH
Credo Semiconductor (HK) LTD	MACOM Technology Solutions	SiFotonics Technologies Co., Ltd.
Dell, Inc.	Marvell Semiconductor, Inc.	Socionext Inc.
DustPhotonics	Maxim Integrated Inc.	Source Photonics, Inc.
EFFECT Photonics B.V.	MaxLinear Inc.	Spirent Communications
Eoptolink Technology	MediaTek	Sumitomo Electric Industries, Ltd.
Epson Electronics America, Inc.	Meta	Sumitomo Osaka Cement
ETRI	Microchip Technology Incorporated	Synopsys, Inc.
EXFO	Microsoft Corporation	TE Connectivity

Foxconn Interconnect Technology Ltd	Mitsubishi Electric Corporation	Telefonica S.A.
Fujikura	Molex	TELUS Communications, Inc.
Fujitsu	Multilane Inc.	US Conec
Furukawa Electric Japan	NEC Corporation	Viavi Solutions Deutschland GmbH
Global Foundries	NeoPhotonics	Wilder Technologies, LLC
Global Unichip Corp (GUC)	Nitto Denko Corporation	Xelic
Google	Nokia	Xilinx
Hakusan Inc	NTT Corporation	Yamaichi Electronics Ltd.
Hewlett Packard Enterprise (HPE)	Nubis Communications, Inc.	ZTE Corporation