LCO：Enabling Next-Gen 400W Pluggable Optics Cooling

White Paper

Liquid Cooling Optics (LCO) is an emerging technology that addresses the increasing thermal challenges of next generation pluggable optics. This white paper examines various LCO architectures and identifies the advantages of Head-side LCO in compatibility with fly over cables, leakage risk management, and dust inspection and cleaning.

Thermal Density Challenge

The rapid growth of AI computing has been driving demand for higher-bandwidth optical interconnects. To fulfill this demand, one direction is the deployment of CPO/NPO transceivers, and the other is the deployment of pluggable modules.

For pluggable modules, there are two main approaches to achieving higher aggregate bandwidth: increasing the number of lanes or increasing lane speed. An example of the former is the 64 lane XPO form factor, while an example of the latter is the 400 Gb/s per lane OSFP/OSFP XD form factor with 8 or 16 lanes. Both approaches face two major challenges: high speed signal integrity and thermal management.

Traditional cooling solutions, whether riding heatsinks or riding cold plates, introduce significant thermal resistance between the pluggable module and the cooling device, thereby reducing the heat extraction capability of the assembly. This is the fundamental reason why the cooling capacity of riding cold plates for widely used pluggable module form factors, such as OSFP and QSFP DD, is limited to around 40 W despite the use of liquid cooling.

This white paper presents a solution that increases cooling capability without abandoning the pluggable module ecosystem.

Liquid Cooling Optics （LCO）

One emerging approach to eliminating the significant thermal resistance caused by the sliding interface between the cold plate and the optical module, while preserving the benefits of liquid cooling, is integrated cooling, also referred to as Liquid Cooled Optics (LCO). In the LCO architecture, the liquid-cooling structure is integrated into the pluggable optical module, and the module is equipped with fluidic quick-connects that allow the system to circulate coolant through the module. This reduces the thermal resistance from the heat sources, such as lasers and chipsets, enabling higher cooling capability for next-generation pluggable modules. Figure 1 shows the conceptual difference between the various types of module cooling technologies.

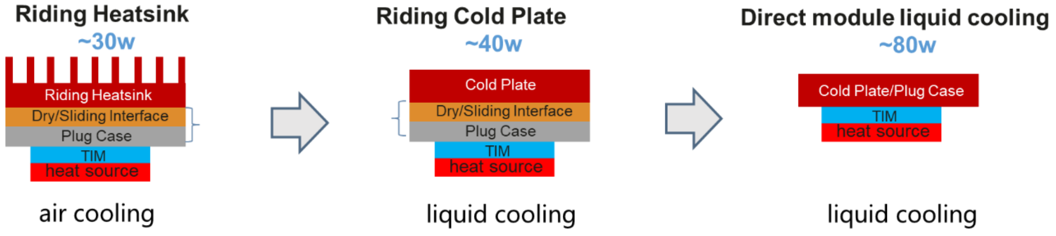


Figure 1: Current pluggable module cooling methods and their thermal capacity

This white paper presents LCO as a promising liquid cooling solution for pluggable optical modules. It also examines the competitive advantages of LCO and its potential to extend the lifecycle of pluggable module form factors, particularly OSFP, OSFP-XD and QSFP-DD.

1. Tail-side LCO

One LCO solution, shown in Figure 2, places the liquid interface at the Tail-side of the pluggable optical module.

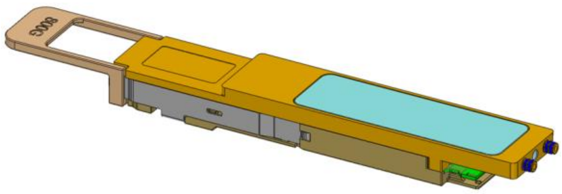


Figure2: Tail-side LCO

2. Head-side LCO

The other architecture, Head-side LCO, is shown in Figure 3. It places the liquid interface at the Head-side of the module, avoiding interference between the electrical and liquid interfaces and providing advantages in dust removal and leakage risk management.

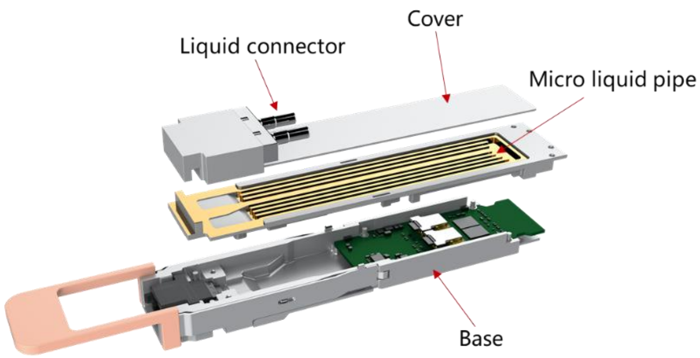


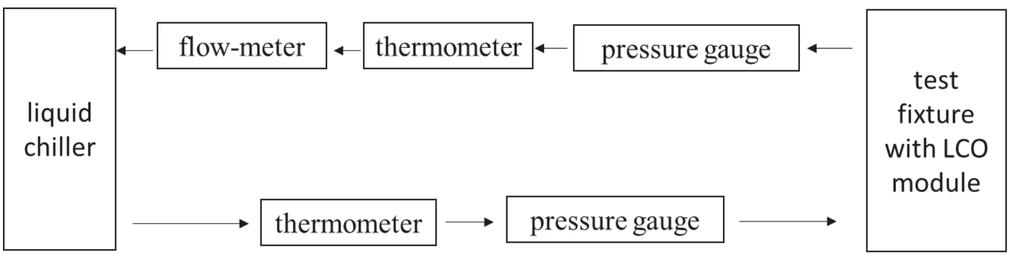
Figure 3: Head-side LCO exploded view

LCO cooling capability

By integrating the cold plate and adding a quick disconnect (QD) liquid connector, the largest source of thermal resistance between the pluggable module and the cold plate is eliminated, increasing the module cooling capability to 400 W for the XPO form factor and 80 W for OSFP, while maintaining an inlet liquid temperature of 45 °C.

Below, we present simulation results and test data demonstrating the thermal dissipation performance of LCO when implemented in the OSFP form factor.

The test setup is shown in the figures below. Thermometers, flow meters and pressure gauges are added in the test loop.



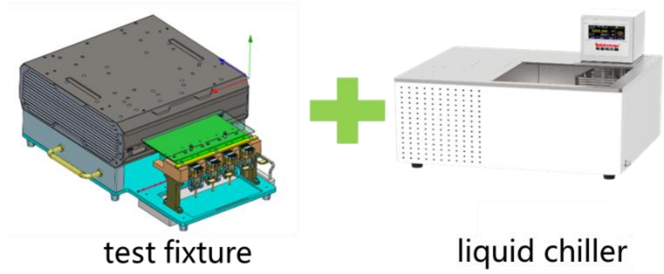


Figure 4: test setup

An OSFP module with implemented LCO was tested using our test fixture . Inside the module, 5 heater blocks were arranged on the PCB, with 3 on top and 2 on bottom, to simulate Optical Digital Signal Processor (ODSP), Optical Subassembly (OSA), DC/DC power and other circuits.

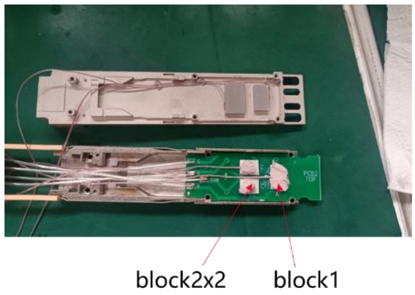


Figure 5: Test board layout

The detailed test conditions are:

1) Liquid coolant material: 25% glycol;

2) Inlet liquid temperature: 45 °C;

3) The heater block power distribution was 65.7% for ODSP, 14.7% for OSA, 9.8% for DC/DC power, and 9.8% for other circuits, simulating a typical coherent pluggable module.

The total module power dissipation capability was limited to 29.7 W by the heater block capability. The thermal resistance of the OSA was calculated from the test data. By setting the OSA power to 14.7% of the total module power, the theoretical maximum cooling capability was then calculated, as shown in the figure below. With an inlet flow of 150 mL/min and an inlet liquid temperature of 45 °C, an OSFP module with LCO can support more than 80 W of power dissipation.

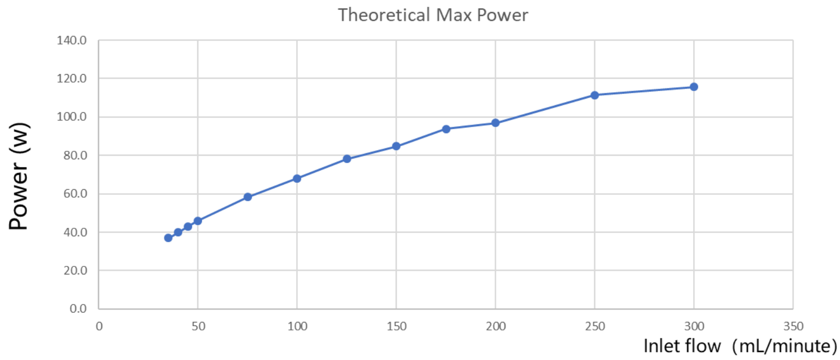


Figure 6: Thermal cooling capability calculated from test data

Liquid and electrical interface

As electrical interface speeds increase from 200 Gb/s to 400 Gb/s and passive path loss requirements become more stringent, electrical fly over cables are expected to see broader use and become essential in many 400 Gb/s implementations for connecting pluggable optical modules to the system's main chip.

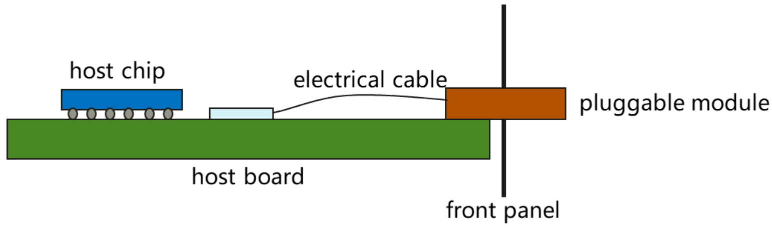


Figure 7: Electrical cable connecting the host chip

However, electrical cables positioned at the back end inevitably interfere with a liquid connector located at the tail side.

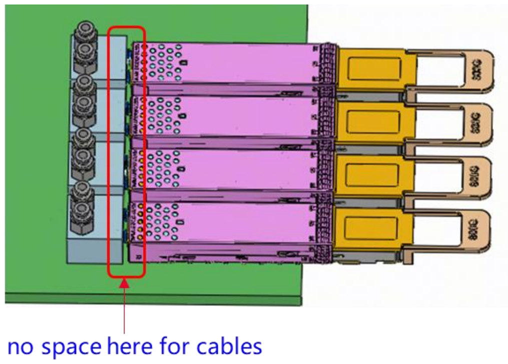


Figure 8: No space for electrical cables for Tail-side LCO

Emerging denser modules such as XPO with more data channels solve this problem by increasing the module width and height, providing space for a liquid interface without interference with electrical cables.

Is there a solution for currently widely used standard form factors, such as OSFP, OSFP-XD, QSFP-DD, etc? Head-side LCO provides such a solution. The liquid cooling mating interface is strategically positioned on the optical port side of the module, thereby inherently avoiding physical interference with electrical cables. This separation simplifies cabling and reduces the risk of mechanical strain on electrical connections.

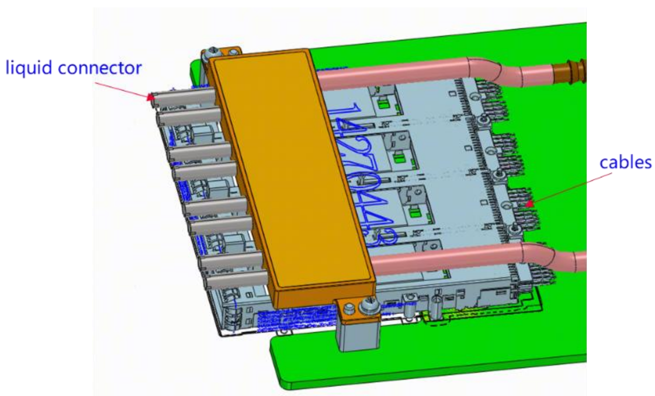


Figure 9: Head-side LCO liquid mating interface and electrical cables separation

Leakage Risk Management

As LCO based solutions emerge, liquid quick disconnect connectors are being used over the host board for the first time. The host board contains many critical components and circuits that are sensitive to coolant leakage. Coolant leakage can lead to serious failures, including short circuits and component corrosion, and may create additional safety hazards.

The Tail-side solution increases this risk.

The Head-side solution, in contrast, provides greater robustness and minimizes leakage by locating liquid interfaces at the front end of the pluggable module, with the liquid mating interface extending beyond the front panel of the system. In the unlikely event of a minor leak, the coolant remains confined to the exterior of the module and away from the host board, preventing damage to internal components. This design aligns with industry best practices for liquid cooling, such as the use of QD connectors with blind-mate sealing mechanisms, which are validated through rigorous cycling tests to ensure reliability. In addition, drip collection tray could be added outside of the front panel within the rack, making liquid connection, leak detection, and remediation simpler.

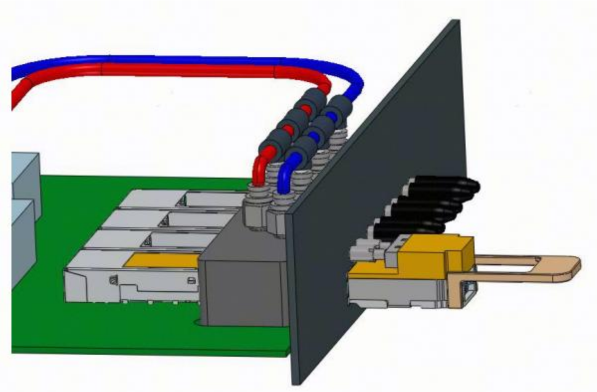


Figure 10: Head-side LCO host side liquid connector stretching out of front panel

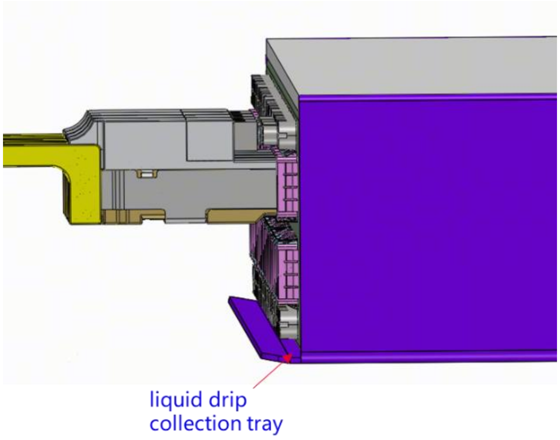


Figure 11: Liquid drip collection tray design example

Dust Inspection and Maintenance Efficiency

Both the liquid mating interface and the liquid loop, including the tiny liquid tunnel within the module cover and the liquid pipes of the host, are very sensitive to dust or other contamination, which can restrict or block liquid flow, degrading cooling performance, increasing liquid pressure, and potentially causing microbial growth within the liquid paths.

During the life cycle of an LCO solution, from installation and operation through maintenance, failure, and replacement, it is very likely that contaminants will reach the liquid interface. Unfortunately, the Tail-side design cannot easily address this issue, as a quick disconnect located deep within the system cannot easily be inspected or cleaned.

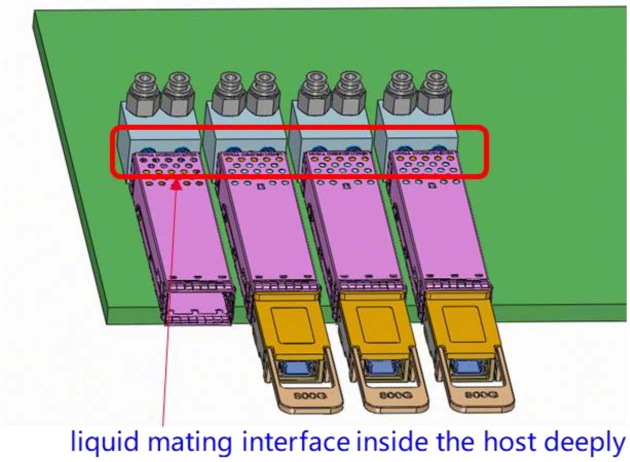


Figure 12: Tail-side liquid mating interface located deep inside the host

Head-side LCO’s liquid interface, with the liquid interface extending beyond the front panel, enables easy visual inspection and removal of dust or other contamination. It reduces maintenance downtime and ensures long-term thermal efficiency, as dust accumulation on cooling surfaces is promptly addressed though maintenance performed outside of the front panel.

Additionally, a dust proof cap can be added, keeping the liquid interfaces clean on both host side and module side.

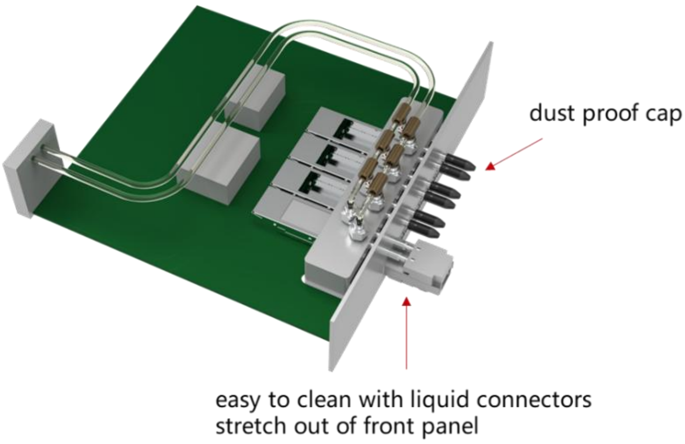


Figure 13: Head-side LCO inspection and cleaning, with a dust proof cap on the host side

Figure 14: Dust proof cap for Head-side LCO

Liquid and Optical interface

Compared with legacy pluggable optical transceivers, LCO leverages the top cover to integrate the cold plate, which increases the cover thickness from 0.6 mm to about 2.0 mm.

Small size connectors, such as VSFF, provide more space and design flexibility for Head-side LCO with liquid connectors near the optical interface.

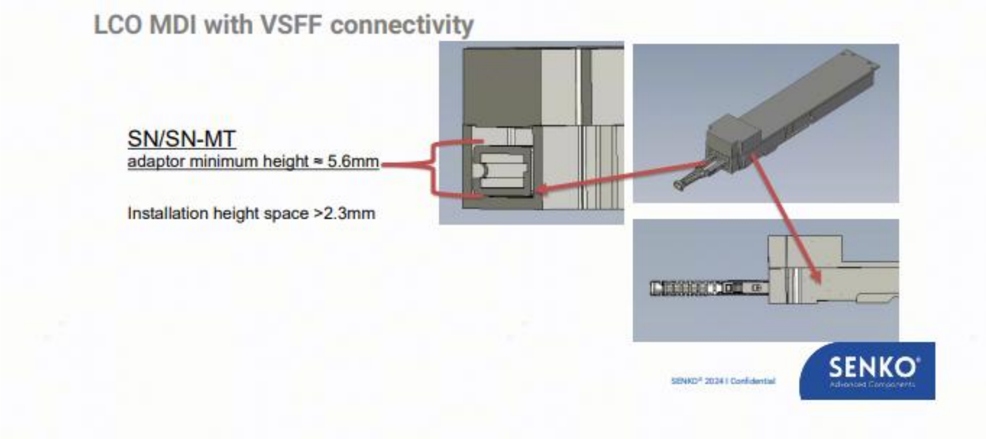


Figure 16: VSFF optical interface provides more space for liquid interface

Double density LCO

As shown in Figure 17, for Head-side LCO, a dual PCB configuration with a cold plate in the middle is possible within the OSFP-XD size, doubling the density and throughput of the module.

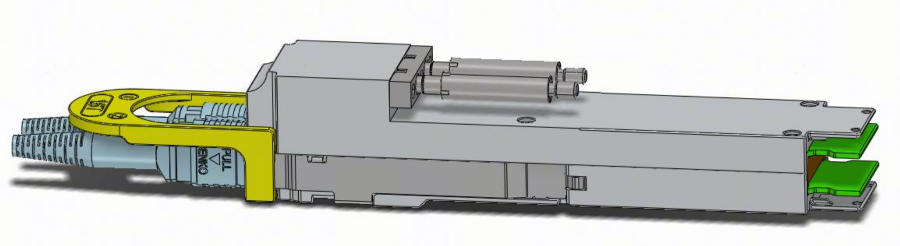


Figure 17: Double PCB LCO

ELSFP application

External Laser Source Small Form Factor Pluggable (ELSFP) has the same air cooling and riding cold plate cooling limit as OSFP, approximately 40 W. LCO is also an optimal solution to increase the power limits of ELSFP.

Compared to the traditional pluggable optical module, ELSFP does not transmit high speed electrical data, and there is no concern about interference between the liquid and electrical cable, as electrical cables are not needed. However, the ELSFP has additional optical connectors above the electrical connector, which still cause interference with the liquid interface. Moreover, for the Tail-side solution, liquid leakage also brings risk for the optical mating surface.

Head-side LCO is an ideal option to address the above concerns of interference and liquid leakage.

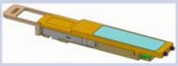
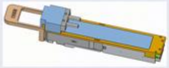
Solution	Scheme	Interference risk with current ELSFP host o/e connector	Liquid leakage risk to host o/e connector	Dust inspection/clean
Tail-side LCO		Yes	Yes	Difficult
Head-side LCO		No	No	Easy by visual

Figure 18: LCO comparison for ELSFP application

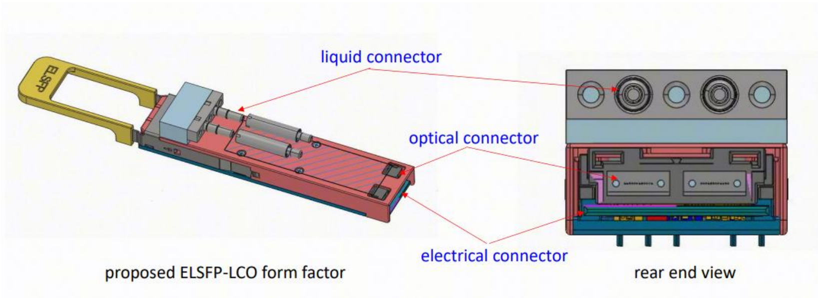


Figure 19: Head-side LCO for ELSFP

Liquid Connector

Blind mate quick disconnect (QD) connectors have been developed by the industry over several years, and are used in the XPO (Tail-side LCO) form factor.

Due to limited space on the front panel of the host system, Head-side LCO requires a more compact QD connector. Prototypes and technologies have been developed and tested by industry partners and are ready for standardization and LCO applications.

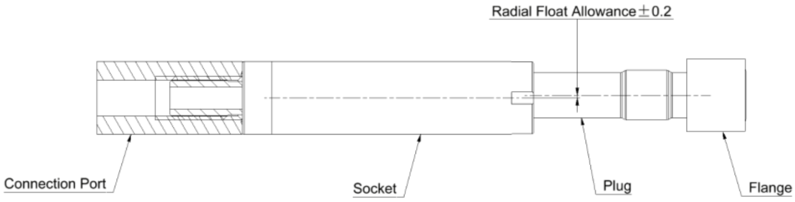


Figure 20: example of Head-side LCO QD connector

System application

32 LCO with OSFP or OSFP-XD form factor can be placed belly to belly or stacked in 1RUx19inch host card, to achieve 100T @3.2T per module, and 200T@6.4T per module, in one RU.

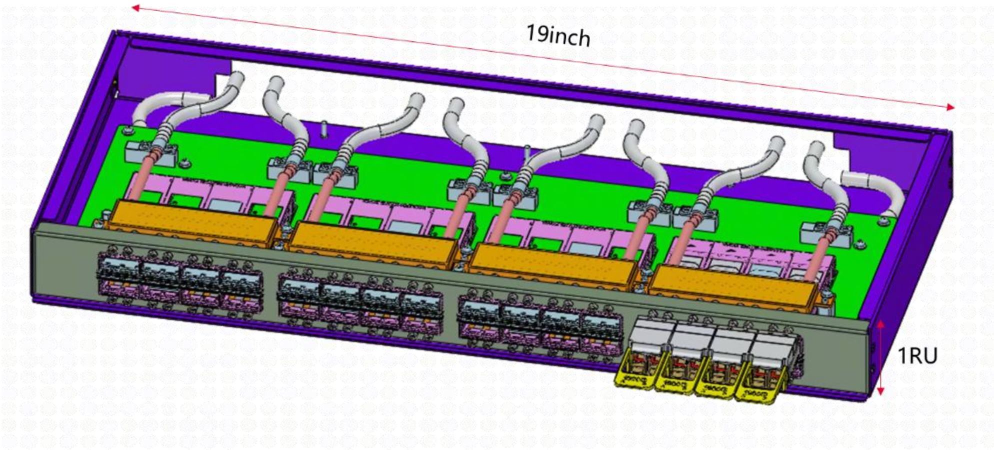


Figure 21: 32 LCO belly to belly layout in 1RU

For stacked LCO, the host manifold can be integrated into the host front panel, to save space for manifolds inside of the host.

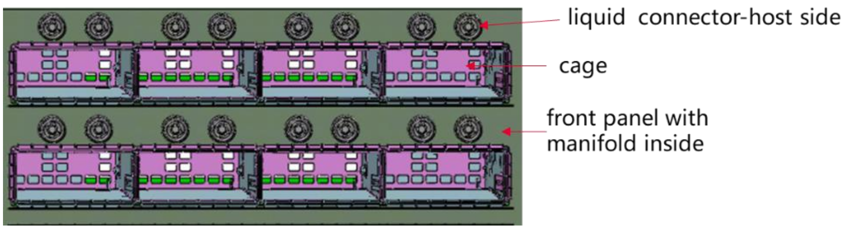


Figure 22: Front panel with manifold inside

Standardization

LCO can be applied to many pluggable form factors, including OSFP, OSFP-XD, QSFP-DD, and ELSFP. To enable broad industry adoption and interoperability, key elements of the LCO interface, including the liquid mating interface and its mechanical requirements, should be standardized across these form factors.

Summary

Head-side LCO offers advantages in electrical cable management, leakage control, and dust removal for mainstream industry form factors (OSFP, OSFP-XD, QSFP-DD).

The time is right for the industry to collaborate and standardize Head-side LCO through relevant standards organizations, to meet the demands of the pluggable optical module market in the AI era.