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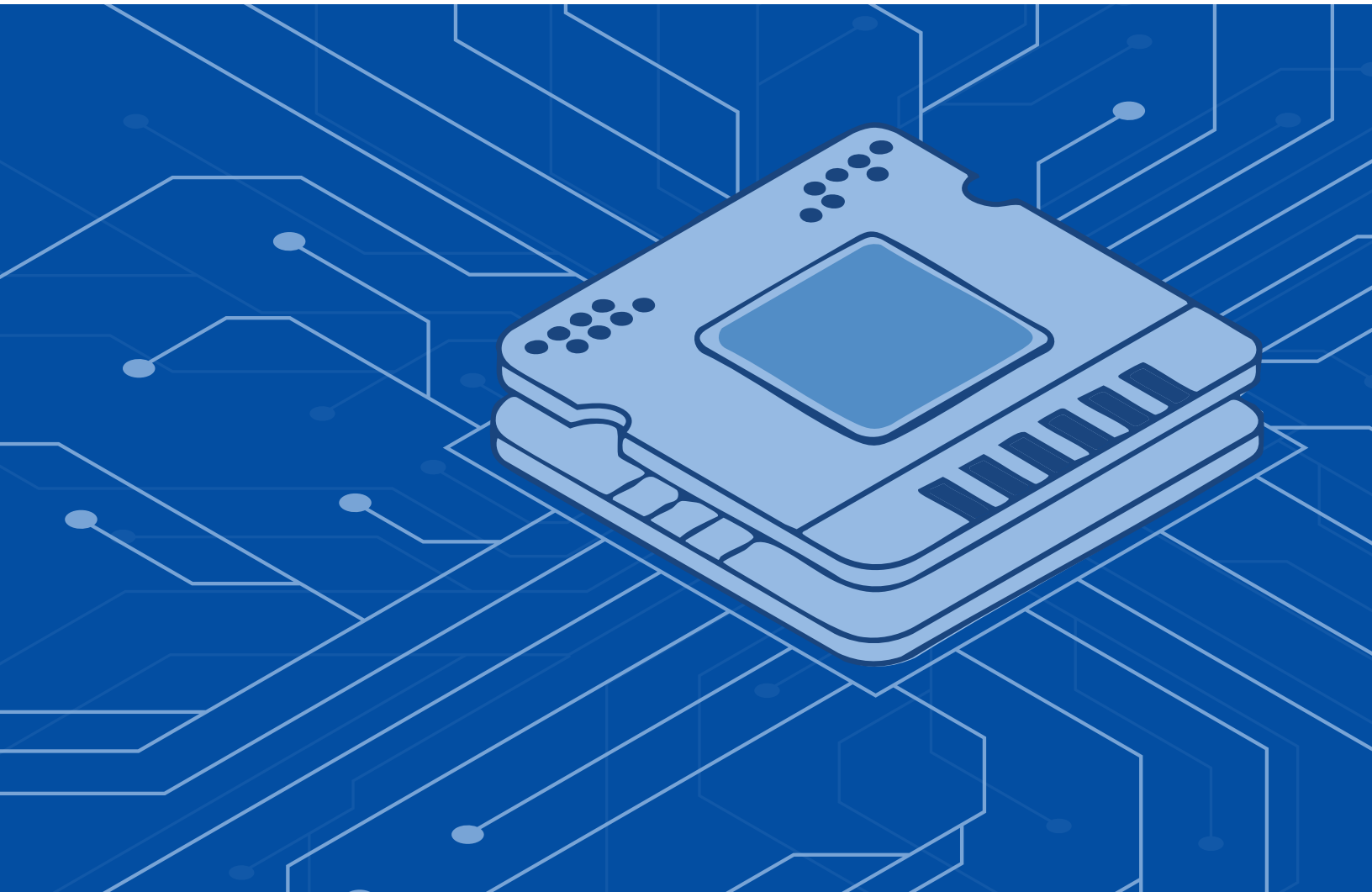
Evolution of Optical Interconnect Architectures:

ELSFP, NPO, CPO and the Role of MT Ferrules

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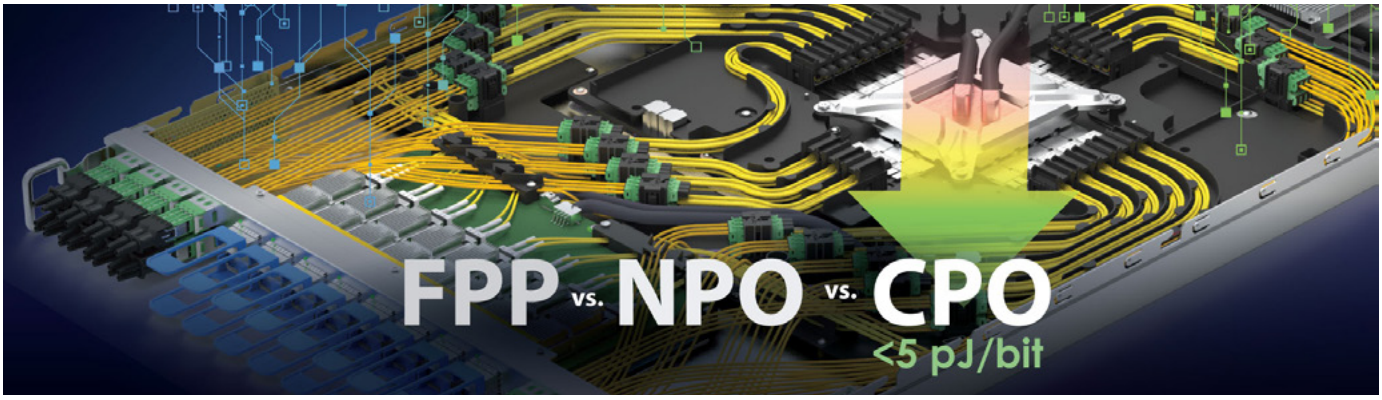
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Evolution of Optical Interconnect Architectures: ELSFP, NPO, CPO and the Role of MT Ferrules

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Why Industry is Migrating from Pluggable Optics to Co-Packaged Optics

The networking industry is undergoing a fundamental architectural transition driven by unprecedented bandwidth growth in hyperscale AI, machine learning (ML) and high-performance computing (HPC) clusters. Modern AI training systems no longer consist of isolated servers exchanging modest amounts of data. Instead, they rely on thousands of GPUs and accelerators operating as a distributed computing fabric where communication bandwidth increasingly becomes the limiting factor. As switch ASIC capacities scale from 12.8 Tb/s to 25.6 Tb/s, 51.2 Tb/s, 102.4 Tb/s and beyond, the traditional front-panel pluggable optics model faces significant technical and economic challenges.

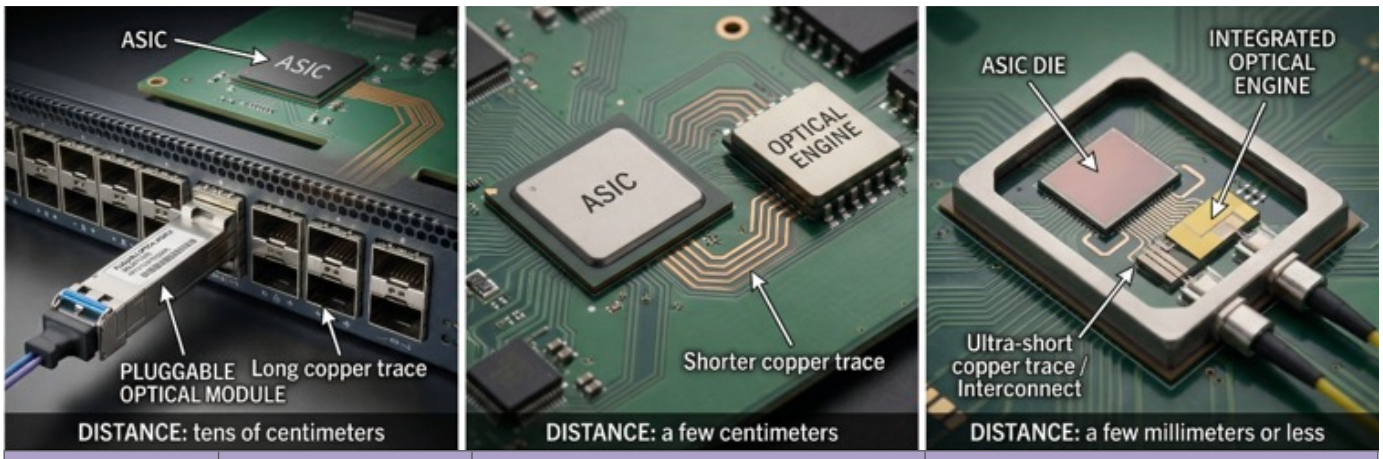
Historically, optical transceivers such as SFP, QSFP and more recently OSFP placed the optical engine at the front panel while the switch ASIC remained near the center of the printed circuit board. This architecture forces high-speed electrical signals to travel relatively long distances across the PCB. At data rates of 112 Gbps PAM4 and the emerging 224 Gbps PAM4 generation, PCB traces can no longer be viewed as simple wires. They behave as high-frequency transmission lines where copper losses, dielectric absorption, reflections, crosstalk, and impedance discontinuities significantly degrade signal quality.

A useful analogy is to envision the PCB as a network of copper antennas embedded in an FR4 fiberglass sponge. At lower frequencies, signals propagate through the board with relatively little degradation. As frequencies increase beyond 50 GHz and approach 100 GHz and higher, a portion of the signal energy is absorbed by the FR4 dielectric while other portions radiate, reflect, or couple into neighboring structures. The result is increased insertion loss, signal distortion, and eye diagram closure. Eye diagram closure directly impacts bit error rate (BER). As the eye becomes smaller due to attenuation, jitter, noise, and inter-symbol interference, the receiver has less timing and voltage margin to reliably distinguish between logic states. This increases the probability of bit errors and can ultimately limit the achievable data rate and link performance. To compensate, system designers must employ sophisticated equalization, clock-data recovery circuits, retimers, and DSPs. While effective, these functions consume substantial power, add latency, increase thermal load plus significantly raise system cost.

At the heart of the system is the switch ASIC. The ASIC performs packet switching and data processing while relying on Serializer/Deserializer (SerDes) interfaces to convert wide parallel internal data buses into very

high-speed serial electrical lanes. The ASIC must drive these signals across the PCB to the optical module and then recover them on the receive side. As trace lengths increase, the SerDes must operate with stronger equalization and higher drive levels, causing power consumption to increase dramatically. In many next-generation switches, the power required to move bits electrically across the board approaches the power required to transmit those bits optically.

The industry's first response was the migration from QSFP to OSFP, which provided a larger thermal envelope capable of supporting 800G and future 1.6T modules. However, OSFP still retains the long electrical path between the ASIC and optical engine. The next evolutionary step is ELSFP (External Laser Small Form Factor Pluggable), which separates laser generation from optical modulation. By relocating high-power lasers into serviceable pluggable modules, ELSFP addresses both thermal management and laser reliability challenges while enabling higher-density optical architectures.



	PLUGGABLE	NPO (Near-Packaged Optics)	CPO (Co-Packaged Optics)
Integration	Low	Low	High
Distance	Medium	Medium	High
Power efficiency	Medium	Short copper trace	Ultra short copper trace/interconnect
Bandwidth density	Medium	Minimum bandwidth density	High
Testing difficulty	Low	Moderate	High

Figure 1 Evolution of optical transceivers packaging Pluggable vs NPO vs CPO

Beyond ELSFP, Near-Packaged Optics (NPO) moves optical engines much closer to the ASIC. Instead of traversing tens of centimeters of lossy PCB routing, electrical signals travel only a few centimeters. This substantially reduces channel loss and decreases the burden on retimers and equalizers. The ultimate evolution is Co-Packaged Optics (CPO), where optical engines are integrated directly adjacent to or within the ASIC package environment. Electrical interconnect lengths shrink from tens of centimeters to only millimeters, enabling Extra Short Reach (XSR) interfaces and dramatically reducing SerDes power consumption.

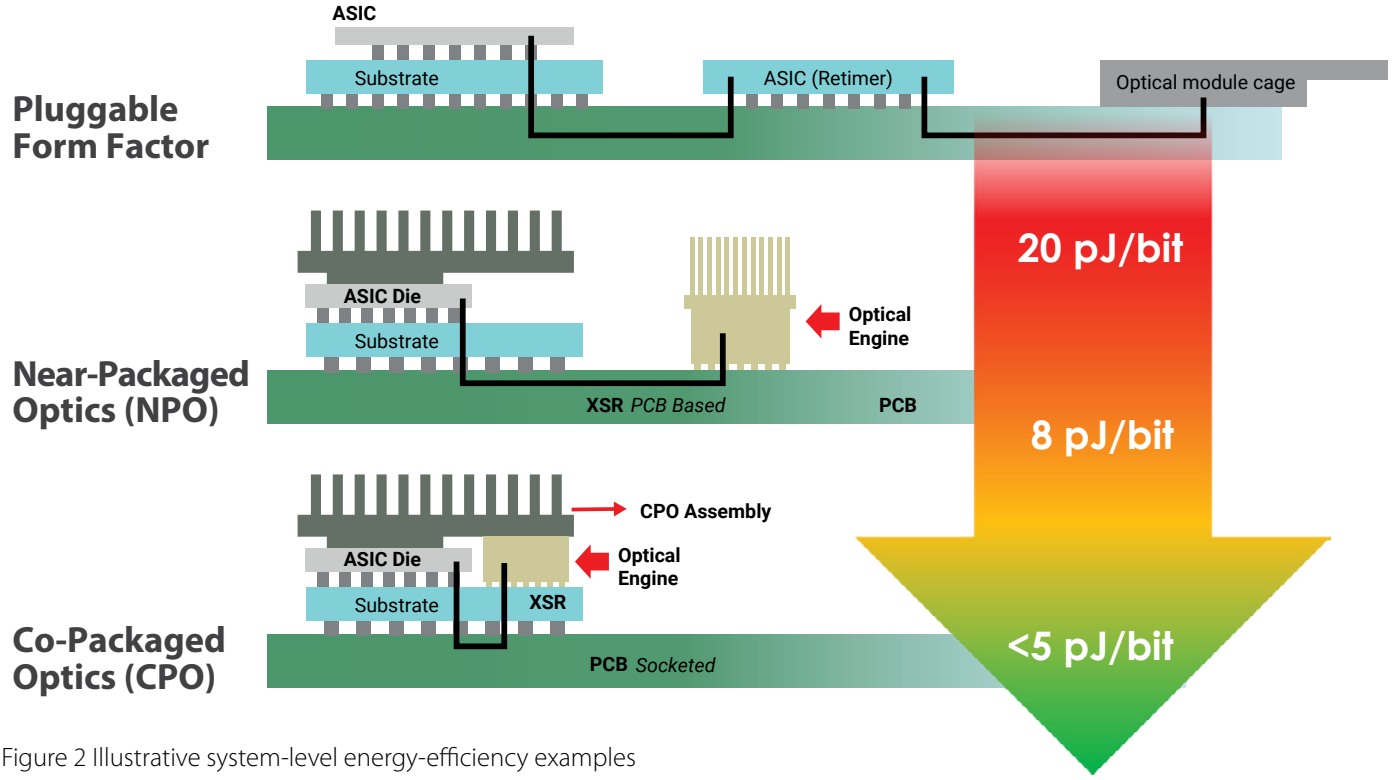
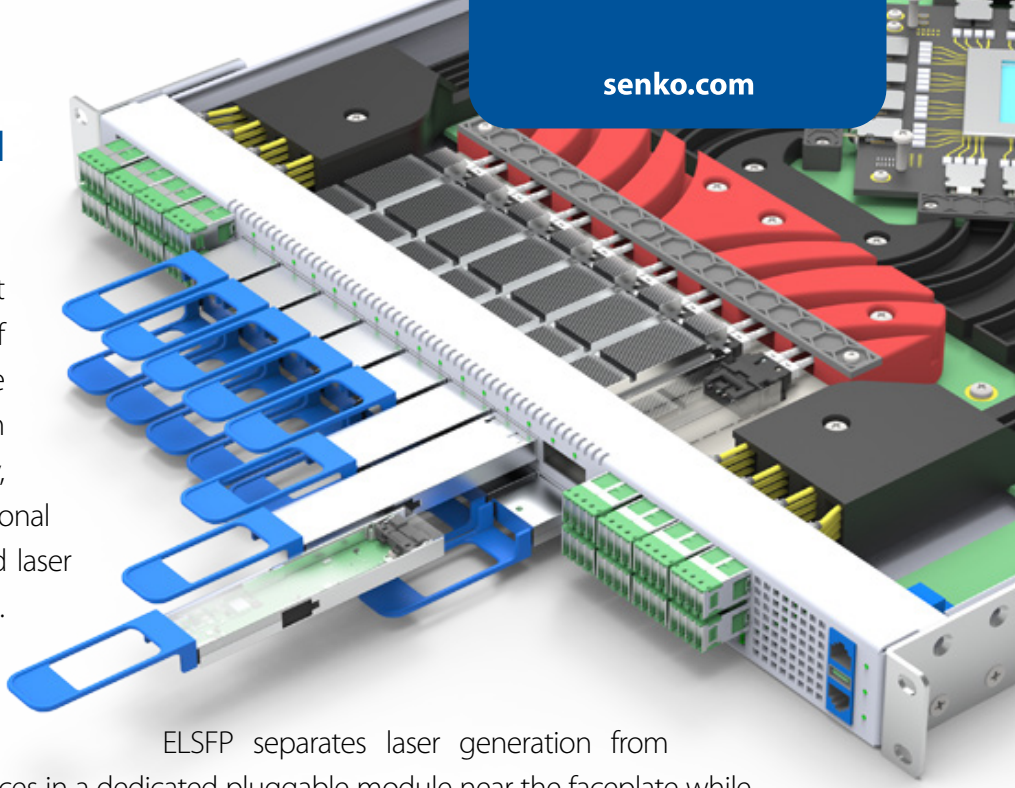


Figure 2 Illustrative system-level energy-efficiency examples

The transition toward CPO is fundamentally an energy-efficiency initiative. Traditional pluggable architectures can consume several additional watts per port solely to overcome board-level electrical losses. As systems scale to hundreds or thousands of ports, these losses translate into significant operational costs and cooling requirements. By eliminating long electrical channels, reducing retimer usage, and minimizing DSP overhead, CPO can reduce interconnect energy consumption from approximately 20 pJ/bit to below 5 pJ/bit.

For hyperscale operators, the migration path from OSFP to ELSFP, NPO and ultimately CPO is not simply about achieving higher bandwidth. It is about sustaining future AI infrastructure growth within practical power, thermal and density constraints. As switch bandwidth continues to increase faster than improvements in electrical interconnect technology, moving optics progressively closer to the ASIC becomes one of the few viable paths to support the next generation of data center networking. This reality is driving strong industry investment in co-packaged architectures and the enabling technologies that support them.

ELSFP (External Laser Small Form-Factor Pluggable)



ELSFP separates laser generation from optical modulation by placing laser sources in a dedicated pluggable module near the faceplate while distributing optical power to multiple photonic engines within the switch. This architecture moves a significant heat source away from the switch ASIC and enables failed laser modules to be replaced without impacting the rest of the optical infrastructure. Hyperscalers particularly value this serviceability because a laser failure no longer requires replacement of an expensive switch assembly.

ELSFP represents an evolutionary step that preserves the operational advantages of pluggable optics while addressing three growing challenges in next-generation AI switches: laser reliability, serviceability, and thermal management. In a traditional transceiver, both the optical engine and laser sources are integrated within the module. As data rates increase to 800G, 1.6T and beyond, laser power consumption and heat generation rise substantially.

A key advantage of ELSFP is its ability to centralize optical power generation. Unlike traditional transceivers, where a dedicated laser typically operates near 0 dBm (1 mW) and serves a single channel, an ELSFP module may contain multiple high-power lasers that distribute optical power across numerous wavelengths and optical engines. As the light passes through splitters, multiplexers, photonic integrated circuits (PICs), modulators, connectors, and fiber assemblies, significant optical loss accumulates. To ensure sufficient power reaches each optical engine, total laser output power may approach 20-25 dBm (100-300 mW), roughly 100-300 times greater than a conventional 0 dBm source. These higher power levels are not driven by a fundamental requirement of the ELSFP form factor itself. Rather, they result from the need to overcome losses within a shared optical distribution network while supplying power to multiple channels simultaneously. Centralizing the lasers in a serviceable ELSFP module simplifies thermal management, improves reliability, and allows laser technology to evolve independently of the optical engines and switch silicon.

The MT ferrule is a critical enabling technology within this architecture. High-power optical distribution requires low-loss, highly repeatable, and high-density optical interfaces capable of connecting multiple fibers simultaneously with exceptional alignment accuracy. MT ferrules provide this capability and serve as the foundational optical interface between ELSFP laser modules, fiber-array assemblies, and the optical engines distributed throughout the system. As a result, MT ferrules are not merely beneficial in ELSFP architectures, they are an essential building block that enables efficient optical power distribution, scalability, and serviceability in next-generation AI and hyperscale data center networks.

SENKO has been a pioneer in the development of ELSFP connectivity solutions, introducing a robust, field-serviceable optical interface designed to support the demanding requirements of next-generation co-packaged optics platforms. The solution is engineered for simplified fiber termination and high-density optical connectivity while maintaining the precision alignment required for high-power laser distribution. To ensure compliance with the OIF ELSFP ecosystem, SENKO's ELSFP interconnect solution has successfully undergone key performance and reliability evaluations, including GR-1435-based testing, supporting compatibility with the OIF-ELSFP-CMIS-01.0 management framework and ELSFP system requirements. Today, SENKO continues extensive interoperability testing with multiple optical engines, laser sources and system vendors to ensure seamless cross-platform compatibility and reliable operation across the evolving ELSFP ecosystem.

ELSFP Cleaning and Inspection Considerations

As optical systems progress toward ELSFP with high power lasers, contamination control becomes increasingly critical. Higher optical power levels, tighter optical budgets, and increased coupling sensitivity reduce tolerance to dust and debris within connector interfaces.

Even microscopic contamination can increase insertion loss and contribute to greater mating-to-mating variability. In high-density optical systems, this variability can reduce available BER margin and negatively affect overall system performance.

To address these challenges, SENKO has developed a reliable long-reach ELSFP cleaning solution specifically designed for high-density optical interfaces and blind-mate connectivity environments. The cleaner enables effective contamination removal within ELSFP optical interfaces while supporting simplified maintenance procedures and improved cleaning consistency. By ensuring a clean optical path prior to mating, the solution helps minimize insertion-loss variability, improve repeatability, and maintain long-term optical performance in next-generation AI, hyperscale, and co-packaged optics deployments.

As optical power levels and system density continue to increase, proactive cleaning and inspection practices will become an essential part of ensuring reliable network operation and maximizing the performance of ELSFP, NPO and CPO architectures.

SENKO is also actively studying the effects of lateral fiber misalignment and optical contamination behaviors in high-power laser environments associated with ELSFP and future CPO architectures. As optical power levels increase from traditional transceiver levels to centralized laser sources approaching 20-25 dBm, the impact of contamination particles and alignment tolerances becomes more pronounced. Ongoing research focuses on understanding how dust, debris, ferrule geometry, and fiber-core offsets influence insertion loss, return loss, optical repeatability and long-term reliability under elevated optical power conditions. These

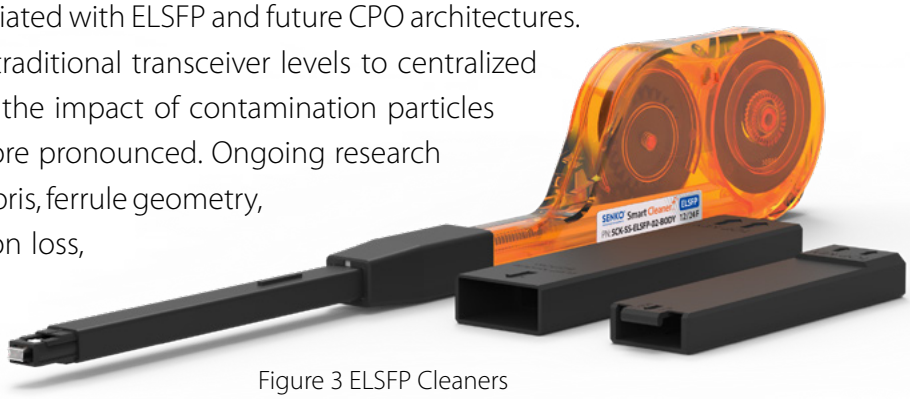


Figure 3 ELSFP Cleaners

studies are helping define best practices for connector design, cleaning procedures and optical interface requirements needed to support next-generation AI and hyperscale networking systems.

ELSFP Advantages

- Maintains familiar hot-swappable pluggable architecture.
- Improves serviceability and field replacement.
- Moves laser heat away from the ASIC.
- Improves laser reliability and simplifies maintenance.
- Supports future 800G, 1.6T and higher-speed systems.
- Compatible with hyperscaler operational models.

ELSFP Disadvantages

- High-speed electrical signals still travel across portions of the PCB.
- Retimers, DSPs, and equalization are often still required.
- Does not fully eliminate board-level power penalties.
- Front-panel density limitations remain.
- Optical and electrical interconnect complexity is still relatively high.

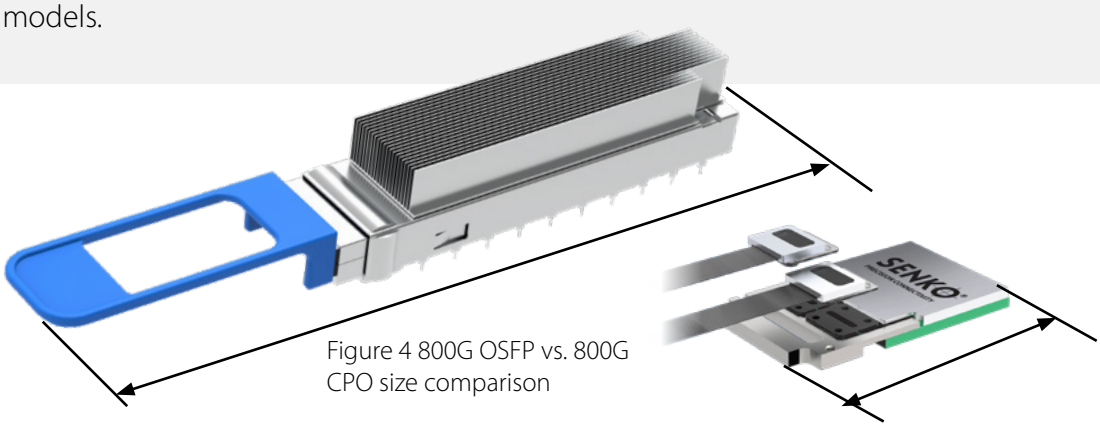


Figure 4 800G OSFP vs. 800G CPO size comparison

NPO (Near-Packaged Optics)

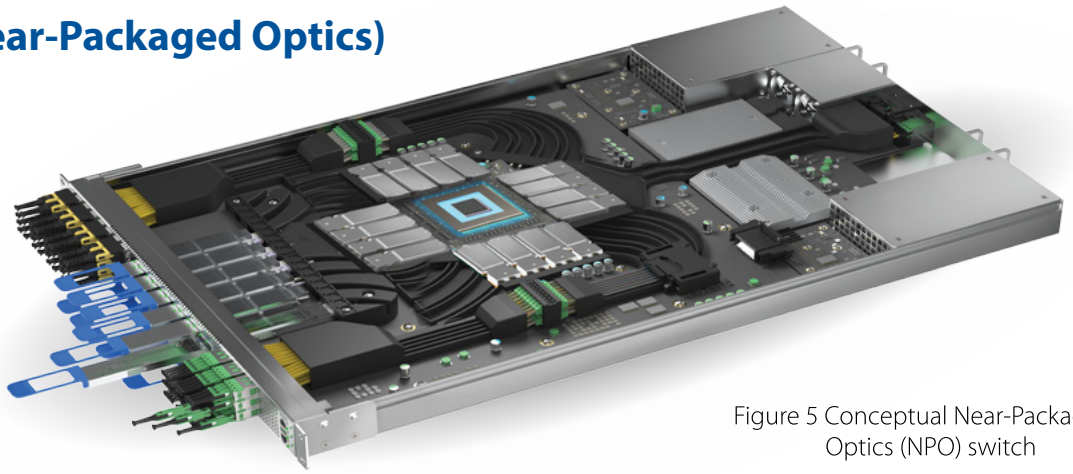
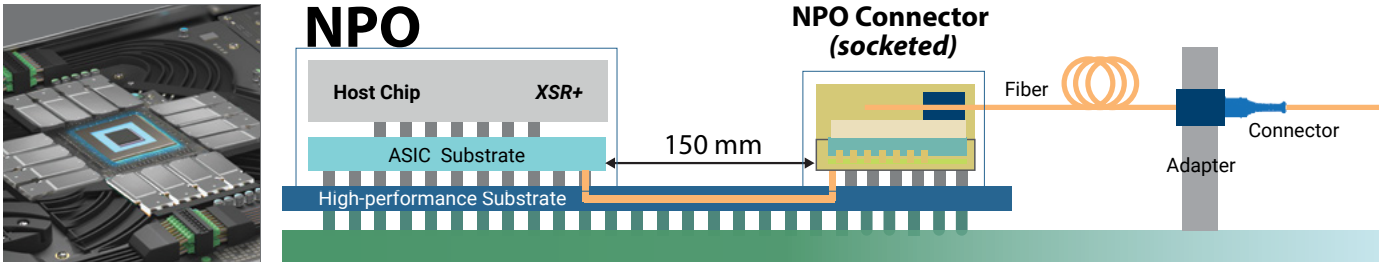


Figure 5 Conceptual Near-Packaged Optics (NPO) switch

Near-Packaged Optics is often viewed as the industry's transitional architecture between pluggables and full Co-Packaged Optics. Rather than positioning optical modules at the front panel, NPO relocates the optical engines physically close to the switch ASIC, typically within a few centimeters.

The optical engines remain separate components from the ASIC package itself, allowing more straightforward manufacturing and service strategies while dramatically shortening the electrical channel. This shorter path reduces insertion loss, decreases signal distortion, and lowers dependence on high-power retimers and equalization circuits. NPO provides many of the electrical efficiency benefits of CPO without requiring the extensive packaging changes associated with integrating optics directly adjacent to the silicon package. It is therefore viewed by many switch vendors as a lower-risk migration path toward future co-packaged systems.



NPO Advantages

- Much shorter electrical paths than OSFP or ELSFP
- Improved signal integrity
- Reduced SerDes power consumption
- Reduced dependence on retimers
- Improves scalability for 51.2T and 102.4T switch generations

NPO Disadvantages

- Optical engines are still discrete devices
- Thermal management becomes more complex as optics move closer to the ASIC
- Serviceability is reduced compared to pluggables
- Savings are significant but not as large as full CPO
- Optical routing inside the chassis becomes more complicated

CPO (Co-Packaged Optics)

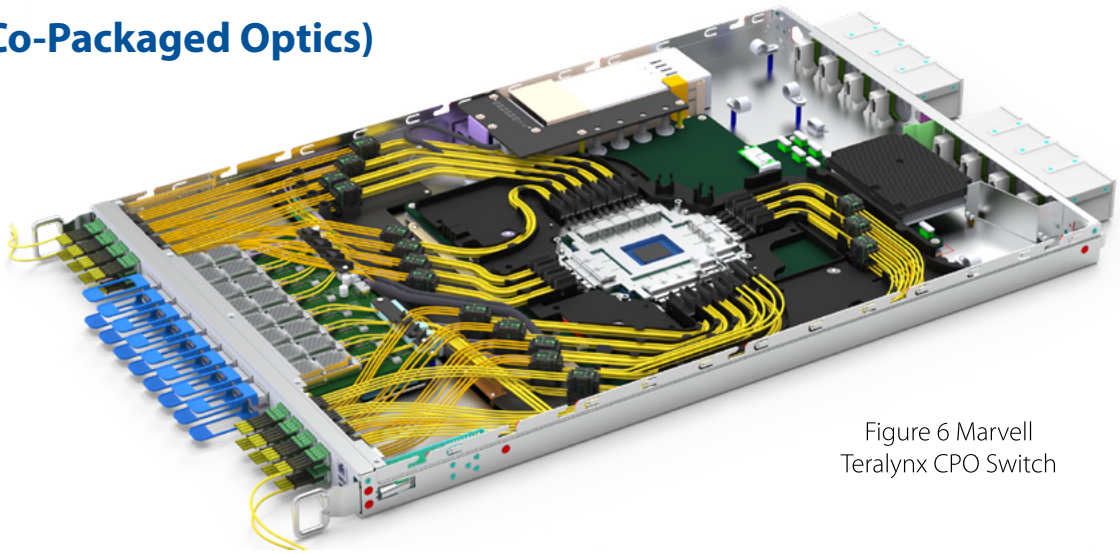
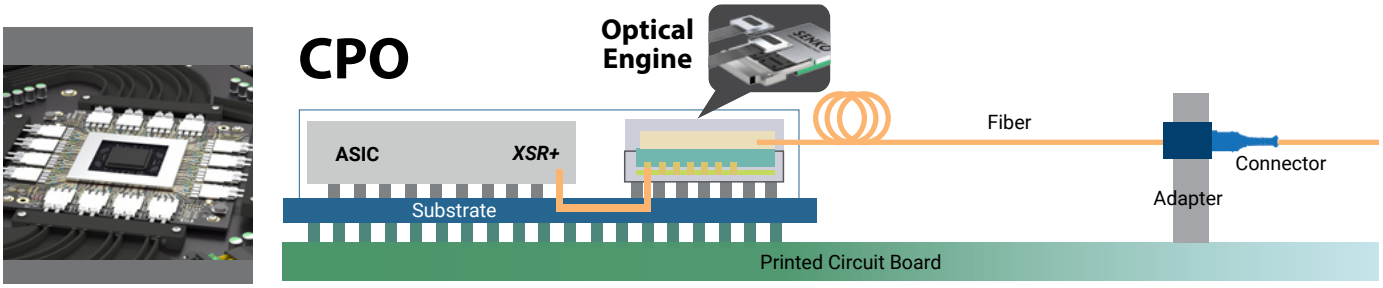


Figure 6 Marvell
Teralynx CPO Switch

CPO represents a leading next-generation architecture being pursued for high-bandwidth AI and hyperscale networking. In CPO systems, optical engines are integrated immediately adjacent to the switch ASIC package, reducing electrical interconnect distances from tens of centimeters to only a few millimeters. Instead of driving signals across a lossy FR4 board, the ASIC communicates through Extra Short Reach (XSR) electrical interfaces directly into nearby photonic devices. This dramatically lowers electrical channel loss and allows the elimination or simplification of retimers, heavy equalization functions, and some DSP overhead. The primary benefit is energy efficiency, reducing interconnect power consumption from roughly 20 pJ/bit toward less than 5 pJ/bit.



As switch bandwidth scales to 102.4T, 204.8T and future AI fabrics, many industry leaders view CPO as one of the few architectures capable of meeting power and density requirements.

SENKO's Cudoform™ PIC connectivity platform is primarily targeted at CPO architectures, where photonic integrated circuits (PICs) are located in close proximity to or directly integrated with the switch package. As electrical interconnect lengths shrink from centimeters to millimeters, the optical interface becomes increasingly critical. SENKO Cudoform™ has developed a compact, high-density, and highly repeatable fiber-to-PIC connection that supports the stringent alignment tolerances required by silicon photonics and co-packaged optical engines. Leveraging SENKO's expertise in MT ferrule technology, the platform enables scalable optical attachment while maintaining low insertion loss, excellent reliability and manufacturability.

Although well suited for advanced NPO implementations, Cudoform™ is particularly valuable in CPO systems where optical coupling precision, thermal stability, and assembly efficiency are essential to achieving next-generation bandwidth and power-efficiency targets.

CPO Advantages

- Lowest electrical channel loss
- Lowest SerDes power consumption
- Significant reduction or elimination of retimers
- Highest front-panel density
- Best long-term scalability
- Enables future 200G/lane and 224G/lane ecosystems
- Lowest energy per transmitted bit

CPO Disadvantages

- Most difficult architecture to manufacture
- Serviceability becomes challenging
- Thermal interaction between optics and ASIC must be carefully managed
- Packaging complexity increases substantially
- Repair and field replacement strategies remain an active industry challenge
- Requires significant ecosystem and supply-chain development

The Industry Progression

The migration path can be simplified as:

OSFP → ELSFP → NPO → CPO

Parameter	OSFP	ELSFP	NPO	CPO
ASIC-to-optics electrical path	15-30 cm	15-30 cm	2-5 cm	<5 mm
Energy efficiency	Lowest	Moderate	High	Highest
SerDes power consumption	Highest	High	Moderate	Lowest
Serviceability	Excellent	Excellent	Moderate	Challenging
Laser replacement	Module replacement	ELSFP replacement	Architecture dependent	Complex
Front-panel density	Moderate	High	Higher	Highest
Packaging complexity	Low	Moderate	High	Very High
Scalability beyond 102.4T	Limited	Improved	Strong	Best

Each step moves optics closer to the switch ASIC and reduces the amount of high-speed electrical signaling traveling through FR4 PCB material. The tradeoff is that every improvement in power efficiency and bandwidth density comes at the cost of increased integration, packaging complexity, and reduced serviceability. Hyperscalers are willing to make this trade because AI clusters are increasingly power-limited rather than bandwidth-limited. As switch ASICs exceed 100 Tb/s, minimizing energy consumed by moving bits becomes just as important as processing them.

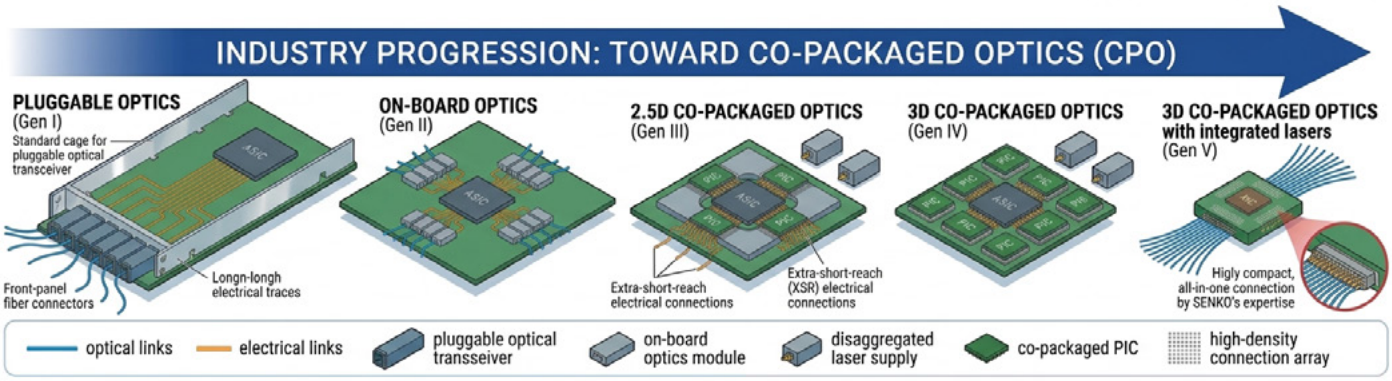


Figure 7 Progression from Pluggables to 3D Co-Packaged Optics (CPO)

MT Ferrules: The Foundation of Optical Connectivity in AI Data Centers

As optical interconnect architectures evolve from OSFP to ELSFP, NPO and ultimately CPO, one component remains remarkably consistent: the MT ferrule. While switch silicon, optical engines and packaging technologies continue to advance, the fundamental challenge of aligning and connecting large numbers of optical fibers with high precision remains unchanged. Consequently, MT ferrules have become the dominant optical interconnect platform across hyperscale data centers.

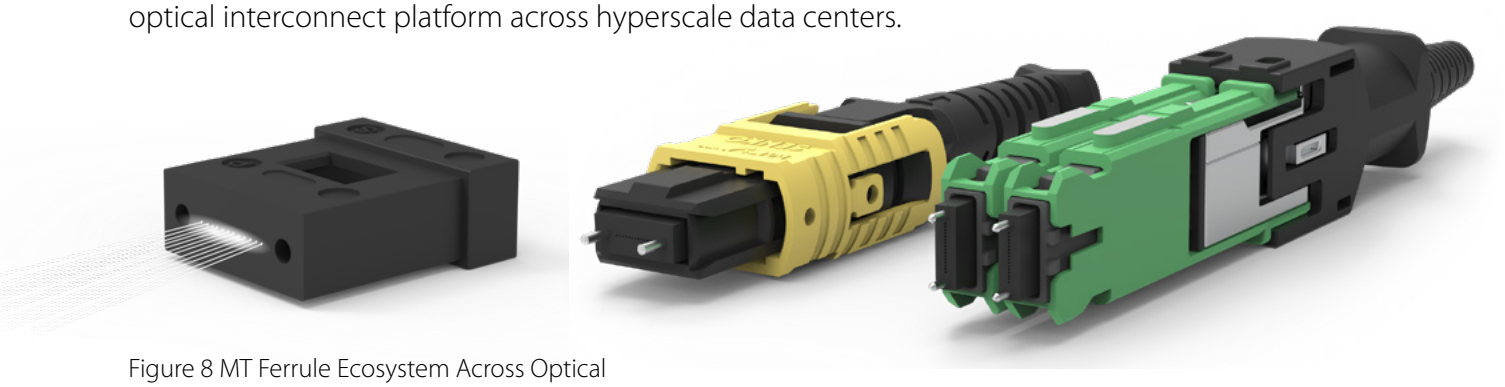


Figure 8 MT Ferrule Ecosystem Across Optical Architectures with SENKO MPO and SN-MT ferrules

To meet ever-increasing bandwidth demands, the industry has standardized on fiber-array architectures rather than individual fiber connections. Ribbon fiber assemblies, MPO and SN-MT trunk cables, breakout assemblies, active optical cables and fiber-array units (FAUs) all rely on MT ferrule technology as their core alignment platform.

The MT ferrule was specifically developed to align multiple fibers within a single interface using precision guide-pin holes and tightly controlled fiber positioning. This enables simultaneous connection of dozens of fibers with low insertion loss, excellent repeatability and high packing density, making MT ferrules ideally suited for AI and hyperscale cloud environments.

A key factor behind MT's widespread adoption is the maturity of its ecosystem. Decades of deployment have established robust standards, automated manufacturing processes, qualified suppliers and well-understood reliability performance. These attributes provide the scalability, supply-chain stability and predictable performance demanded by hyperscale operators.

Importantly, the transition to CPO does not eliminate the need for MT ferrules. Although optical engines move closer to the ASIC, efficient coupling between fibers, lasers, silicon photonics, and photonic integrated circuits still requires precise fiber-array alignment. As a result, many next-generation architectures continue to leverage MT ferrules or MT-derived interfaces for external laser distribution, detachable fiber assemblies and serviceable optical connections.

Additionally, the transition toward NPO and CPO architectures also places new thermal demands on optical interconnect components. High-power ASICs and ELSFP external laser sources can expose fiber interfaces to elevated operating temperatures. Furthermore, many optical engines are assembled using SMT-compatible manufacturing processes that require survival through multiple lead-free solder reflow cycles exceeding 200°C. As a result, next-generation MT ferrules must provide not only precise fiber alignment and low optical loss but also exceptional dimensional stability and reliability under both high-temperature processing and long-term field operation. This has created growing interest in advanced ferrule materials specifically engineered for CPO and silicon photonics applications.

As the industry progresses toward ELSFP, NPO and CPO architectures, many aspects of the optical system will continue to evolve. However, the need for reliable, precise, and cost-effective fiber-array alignment remains constant. For this reason, MT ferrules are expected to remain a foundational building block of optical connectivity in future AI and hyperscale data-center infrastructures.

SENKO's Ongoing Commitment to Advancing Next-Generation MT Ferrule Technology

As ELSFP, NPO and CPO architectures continue to increase optical power density and thermal loading, the performance of the MT ferrule becomes increasingly critical. High-power external laser sources, elevated operating temperatures near ASICs and exposure to lead-free solder reflow processes place new demands on ferrule materials and dimensional stability. Recognizing these challenges, SENKO has invested extensively in the development of advanced MT ferrule technologies, encompassing material science, mold design, precision manufacturing, dimensional control, and long-term reliability testing. The objective extends beyond manufacturing a conventional ferrule to creating a platform capable of maintaining precise fiber alignment, low insertion loss, and repeatable performance under the demanding environmental conditions of next-generation optical systems. Through continuous refinement of ferrule materials and manufacturing processes, SENKO has developed high-performance MT ferrules that support applications ranging from hyperscale AI data centers and silicon photonics platforms to high-reliability aerospace and defense systems.

Low-Loss Performance Through Material and Process Control

Achieving low-loss optical performance requires much more than accurate fiber placement. Every aspect of ferrule production influences final connector performance, including:

Ferrule Performance

- Ferrule material composition
- Thermal expansion characteristics
- Mold precision
- Fiber hole dimensional accuracy
- Guide pin hole tolerances
- Surface quality
- Manufacturing process control

Even minor dimensional variation can affect fiber-core alignment and increase insertion loss. Therefore, low-loss ferrules require strict control throughout the manufacturing process.

SENKO's low-loss MT and SN-MT ferrule design combines optimized ferrule materials with tightly controlled manufacturing practices to maintain precise fiber alignment and consistent optical performance throughout the connector lifecycle. Through decades of MT ferrule development and high-volume manufacturing experience, SENKO has established itself as a technology leader in both ferrule design and validation. Extensive metrology, environmental testing, and process control methodologies are employed to ensure every ferrule meets the increasingly stringent requirements of AI, hyperscale, silicon photonics, ELSFP and CPO applications.

As optical networking transitions from traditional transceivers to highly integrated optical engines, maintaining low insertion loss at scale has become one of the industry's greatest manufacturing challenges. SENKO continues to invest in advanced tooling, automation, process optimization and testing infrastructure to support rapidly growing market demand while maintaining the dimensional precision and optical consistency required for next-generation fiber-array connectivity. This combination of innovation, manufacturing scalability and rigorous qualification has enabled SENKO to successfully ramp MT ferrule production volumes while preserving the performance standards demanded by hyperscale data center operators and leading optical engine manufacturers.

Reliability Under Extreme Temperature Conditions

Many emerging optical applications operate in environments far more demanding than traditional telecommunications systems. Military, aerospace, industrial, ELSFP, NPO and CPO applications frequently require operation across wide temperature ranges while maintaining stable optical performance. In addition, next-generation optical engines are increasingly exposed to higher thermal loads from high-power ASICs

and centralized laser architectures, while some assemblies must also survive lead-free solder reflow processes during manufacturing.

To evaluate ferrule robustness under these conditions, SENKO performed extensive testing of multiple MT ferrule designs capable of supporting extreme temperature exposure. The evaluation included thermal cycling from -55°C to +125°C using a test profile based on GR-1435 environmental testing methodology. Fifteen MPO ribbon assemblies utilizing SENKO's Low-Loss MT ferrule design were subjected to repeated temperature cycling while optical performance was continuously monitored.

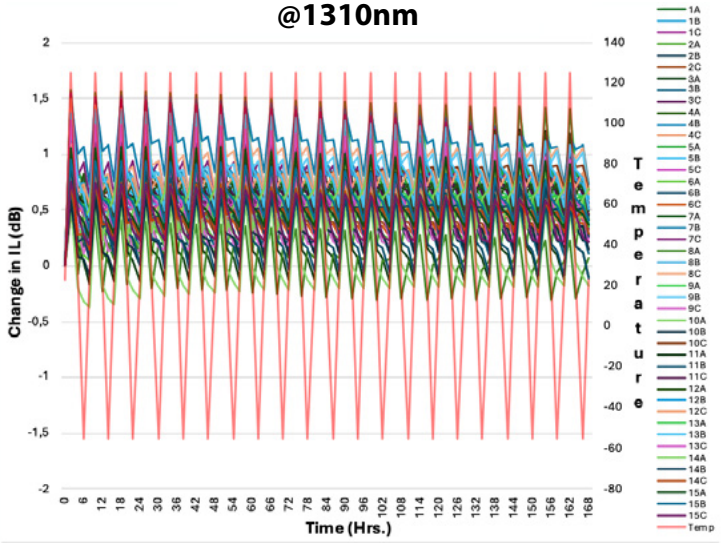
Ferrule Stability Results:

- Average live optical loss change: 0.01 dB
- Maximum observed optical loss excursion: 0.66 dB
- Stable performance throughout the complete temperature cycling profile from -55°C to +125°C

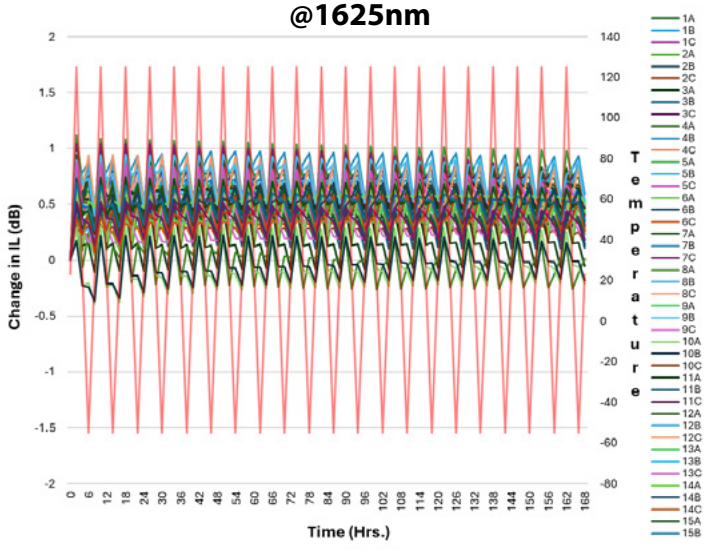
The study concluded that MPO connectors utilizing SENKO low-loss MT ferrules maintained consistent and reliable performance throughout the testing period. Furthermore, the evaluated ferrule design was identified as the most robust ferrule material and construction among the tested groups for extreme-temperature applications.

These results demonstrate that advanced MT ferrule technology can successfully meet the thermal and reliability requirements of emerging ELSFP and CPO architectures, where high-power laser distribution, elevated operating temperatures, and long-term service life place unprecedented demands on optical interconnect components. By combining extensive qualification testing with high-volume manufacturing expertise, SENKO is helping enable the next generation of AI and hyperscale optical infrastructure.

IL Change vs. Temperature @1310nm



IL Change vs. Temperature @1625nm



Conclusion and Summary

As optical interconnects evolve from pluggable optics to ELSFP, NPO and CPO architectures, the need for precise, reliable, and scalable fiber-array alignment remains constant. MT ferrules continue to serve as the foundation of high-density optical connectivity, enabling efficient optical coupling across AI, hyperscale, and silicon photonics platforms.

The adoption of high-power external laser architectures, increasing thermal loads and greater optical integration places new demands on ferrule materials, dimensional stability and manufacturing precision. Through extensive investment in material science, process control, environmental qualification, and high-volume manufacturing, SENKO has developed low-loss MT ferrule solutions capable of maintaining exceptional performance across demanding operating environments.

As a pioneer in ELSFP connectivity and advanced MT ferrule technology, SENKO continues to drive innovation through rigorous testing, interoperability validation, and scalable manufacturing. From traditional MPO connectivity to emerging ELSFP and CPO deployments, SENKO is helping enable the next generation of high-speed optical networks.

SENKO is prepared to support this transition with qualified products, validated termination processes, reference test assemblies, and extensive random-mating and optical-loss testing. Our solutions are designed to help customers maintain signal integrity and BER performance as data rates, optical power levels, and network density continue to increase.

⇨ For more information or technical consultation, contact your SENKO representative.

Biography



Andrei Vankov is a Senior Application Engineer at SENKO Advanced Components with over 30 years of experience in fiber optic communications and optical interconnects. He supports global customers across hyperscale data centers, telecom providers, OEMs and system integrators, provides customer training and solves their technical challenges, with expertise in VSFF interconnects, MPO and single-fiber solutions, co-packaged optics and high-density fiber systems. He holds a BS from Thomas Edison State College and an MSEE from Pennsylvania State University, began his career at Sumitomo Electric Lightwave in Yokohama Japan and later worked as a Senior Optical Design Engineer at Advanced Interconnect where he developed passive components and optical backplanes. Prior joining SENKO team he worked at Nokia RFS supporting LTE RAN deployments and he holds several US and European patents in fiber optic interconnect technology.

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