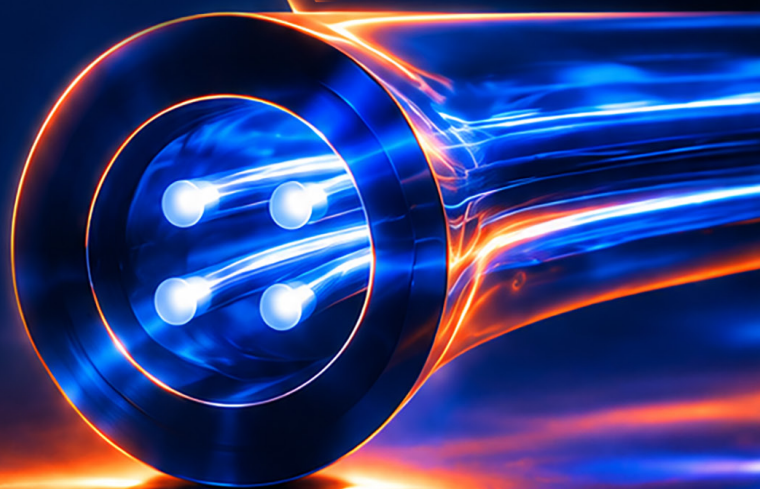




4-Core Multicore Fiber Cable, Connector and Fiber Array Unit Specification

for Transceiver and
Co-Packaged Optic Links

VERSION 1





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Contributing Editors

Advanced Photonics Coalition,
Melissa Kallos, Working Group Facilitator and Editor

Advantest, Shawn Kann, Editor

Alcyon Photonics, Dominik Rabus, Multicore Fiber Group Co-Chairperson

Alcyon Photonics, Panaiot Zotev, Editor

America Fujikura Ltd (AFL), Ted Lichoulas, Editor & Multicore Fiber Group Chairperson

America Fujikura Ltd (AFL), Kikuchi Osamu, Editor

Intel Corporation, Boping Xie, Editor

Lightera, John George, Editor

MPI Corporation, Lawrence van der Vegt, Editor

Synopsys Inc., Sanjay Gangadhara, Editor

A special thank you to Nikhil Angra and Francois Beauregard, former MCF chairpersons



Multicore Fiber Working Group Members

2Pi Optics	Hakusan Inc.	Pilot Photonics Ltd.
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1. Introduction

Multicore Fiber (MCF) packs multiple spatially-isolated light-guiding cores into a single fiber strand. Each core carries an independent optical signal, multiplying the data throughput of a single physical cable. MCF can integrate multiple cores within a single 125 μm cladding — the same outer diameter as standard single-mode fiber. This physical compatibility is strategically important: existing conduit, enclosures, cable management trays, and connector dimensions require no modification. Each core operates in the single-mode regime independently, guiding light with a precise refractive index profile. MCF design examples include 4-core, 7-core (hexagonal packed), and 12- or 19-core configurations. The primary objective of this Multicore Fiber (MCF) Specification is to define specifications for cabling infrastructure that uses 4 core MCF cables and connectors. This specification also defines the connector and FAU interfaces for Transceivers and Co-Packaged Optics.

The application focus is 500 meter and 2 km reach applications within the data center for scale up and scale out networks, that are protocol independent and can be used in Infiniband, Ethernet and UAlink networks

The **APC MCF WG** defines specifications for:

- **Four Core Multicore Fiber with Single-Mode Cores**
- **Four Core MCF Connectors**
- **Cable Polarity And Proposed Cabling Configurations**
- **FAU Specifications For PIC Attachment**
- **System Level Testing Requirements**

2.0 Applications for an End-to-End Multicore Fiber Link

2.1 Background and definitions for application areas

AI/ML Data Centers use a standard leaf/spine architecture to connect to the back-end computer nodes. This architecture comprises numerous interconnections and cross-connections. The space required for fiber and cable in these links can be significantly reduced with multicore fiber links.

2.2 Back-end scale-out and scale-up network in AI/ML

As AI models increase in complexity, greater GPU coordination is needed, requiring high-density, low-latency interconnect for the scale-out and scale-up architectures. Multicore fiber links can increase both cable and connector core density to better utilize the ASIC beachhead.

2.3 Multicore trunk cabling between leaf/spine

Historically, optical transceiver interfaces utilize single core fibers. Multicore native transceivers that can directly accept connectors terminated with MCF are becoming commercially available, facilitating multicore fiber deployments within datacenters. Additionally, these multicore native fiber transceivers are eliminating the need to deploy external FIFOs to merge single core fibers into multicore fibers.

2.4 Shuffle Applications

In high-density AI and High-Performance Computing (HPC) data centers, “shuffle connect” is a compact package of terminated optical fibers (like a Shuffle Box or Multifiber Shuffle Assembly) for organizing and configuring multiple complex fiber optic connections. The primary goal is to simplify fiber routing, minimize cable congestion, reduce latency, and optimize space utilization, particularly in Spine-and-Leaf network architectures. A shuffle connect is an alternative to the explosion of cables that can result from connecting every leaf switch to every spine switch.

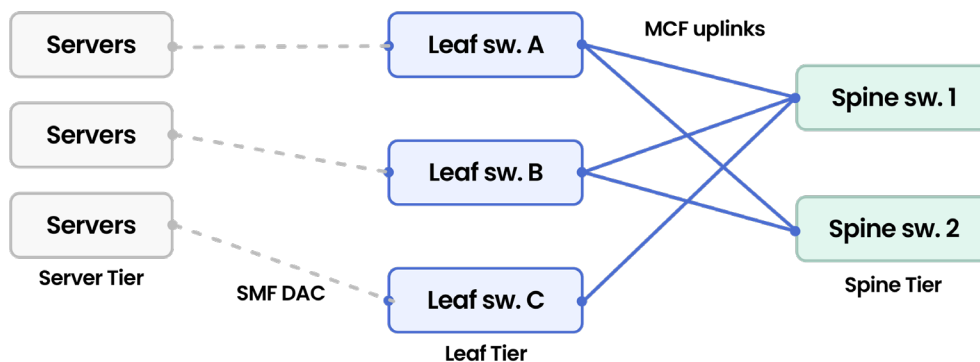


Figure 1 – Diagram of Spine and Leaf Architecture

3.0 Specifications for a 4 core Multicore Fiber

This section describes a 4-core single mode fiber for datacenter application.

3.1 Geometry

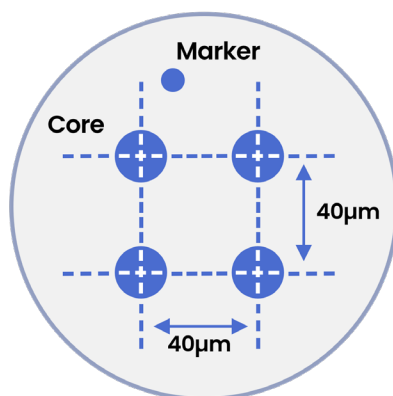


Figure 2 – 4 Core Multicore Fiber Geometry

3.2 Specifications

Parameter		Spec
1	Core Radius	$28.3 \pm 1 \mu\text{m}$
2	Core Pitch	$40 \pm 1 \mu\text{m}$
3	Core Offset	$\leq 1 \mu\text{m}$
4	Marker Diameter	Vendor Specific
5	Marker Position	Vendor Specific,
		Asymmetric
6	Cladding Diameter	$125 \pm 1 \mu\text{m}$
7	Cladding Non-Circularity	$< 1 \%$
8	Coating Diameter (Colored)	$200 \pm 20 \mu\text{m}$
9	Coating/Cladding Concentricity	$< 10 \mu\text{m}$
10	General (except for PMD)	ITU-T G.652.D or G.657.A1
11	Attenuation @ 1310 nm	0.4 dB/km max – excluding point discontinuities
12	Cross Talk (1km)	$\leq -40 \text{ dB (1310 nm)}$

Table 1 – Multicore Fiber Parameters and Specifications

3.3 Conformance

Multicore Fiber claiming conformance to this standard shall provide a completed compliance matrix referencing and listing the measured or characterized value, and the test method used. Conformance claims shall be independently verified by an accredited test laboratory or the vendor's documented quality management system compliant with ISO 9001.

4.0 Specifications for a 4-Core MCF Connector

This section describes the connectivity variants for cabling infrastructure utilized in AI/ML and datacenter applications.

4.1 Fiber Assignment Variants

This document describes two variants of Space Division Multiplexing (SDM) applicable to multi core fiber. Co-propagating systems transmit data in the same direction in all cores on each fiber, Counter- propagating systems transmit data in opposite directions in cores on each fiber. The table below shows Space Division Multiplexing (SDM) Applicable to Multicore fiber, in comparison to single core fiber systems.

	SDM	
Duplex	DWDM	Multicore co-propagation
Simplex	Bi-directional (Bidi)	Multicore counter-propagation

Figure 3 – Space Division Multiplexing (SDM) Applicable to Multicore fiber

4.1.1 A Pattern (Counter Propagating)



Figure 4 – A Pattern - (Counter propagating)

A pattern fiber core mapping Tx 1-32 from left to right; Rx 1-32 from right to left. The implementation of this pattern will require a pair of fibers to complete the Transmit and Receives which are on a pair of fibers as opposed to on a single fiber. Pattern A supports the current single core deployments with a pair of fibers.

4.1.2 B Pattern (Counter Propagating)



Figure 5 – B Pattern

B pattern fiber core mapping Tx1/Rx1 are within the same Multicore fiber. Implementation of this pattern requires a single fiber as the transmit and receive cores are on the same fiber. This pattern is new to the deployment methodology with single core, which requires a pair of fibers (1 for transmit and 1 for receive).

4.1.3 C Pattern (Co-propagating)



Figure 6 – C Pattern - (Co-propagating)

C pattern fiber core mapping all Tx are on the left; All Rx on the right.

4.2 Multi-Fiber Connector

Multi-fiber optical connector interfaces that can be used in the MCF Transceiver or Device are illustrated below. These are illustrated to support 16 fibers / 64 core interfaces (TX: 32x 200G RX: 32x 200G). The VSFF figures refer to trademarks of specific companies identified below. This document is not limited to specific VSFF connectors.

4.2.1 Very Small Form Factor (VSFF) Optical Interface – Senko SN-MT® 16

4.2.1.1 A Pattern

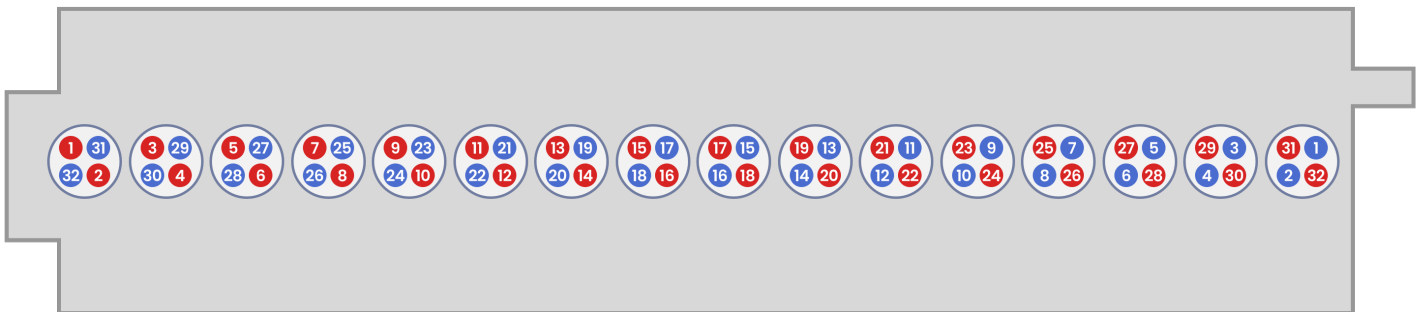


Figure 7 – A Pattern - Optical Interface

4.2.1.2 B Pattern

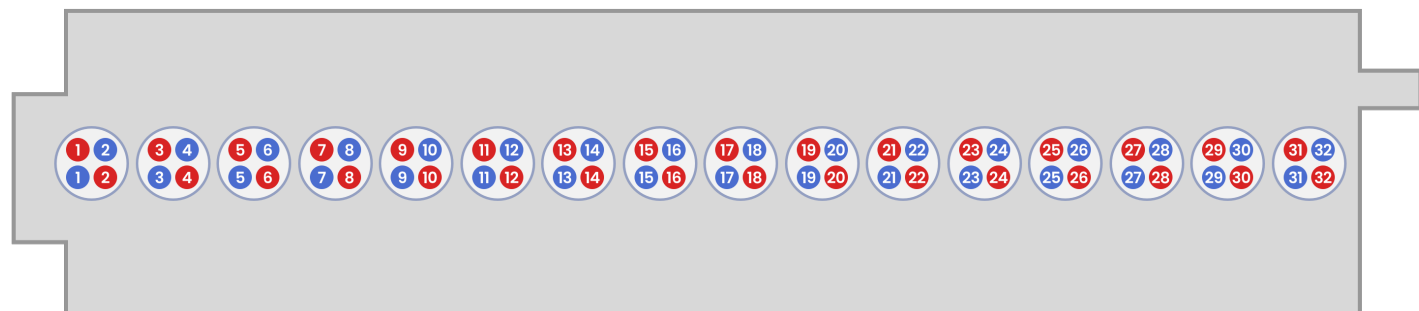


Figure 8 – B Pattern - Optical Interface

4.2.1.3 C Pattern

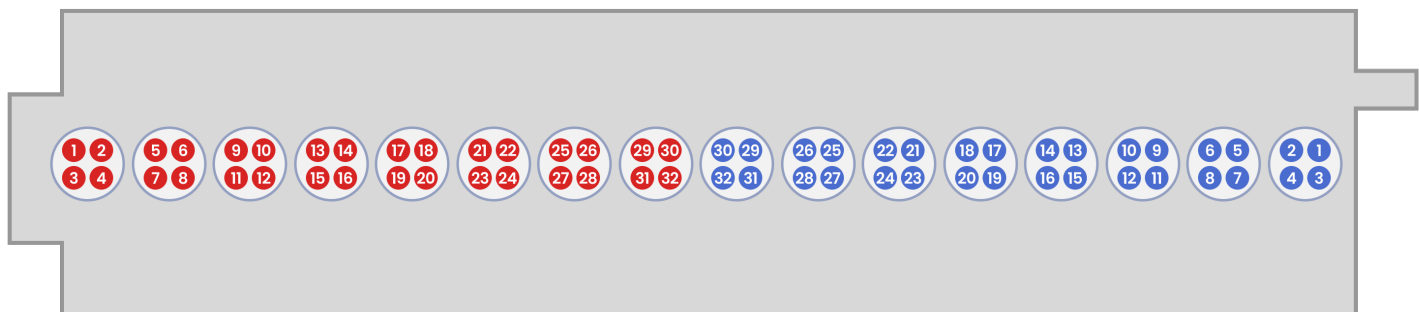


Figure 9 – C Pattern - Optical Interface

4.2.2 Very Small Form Factor (VSFF) Optical Interface

4.2.2.1 A Pattern

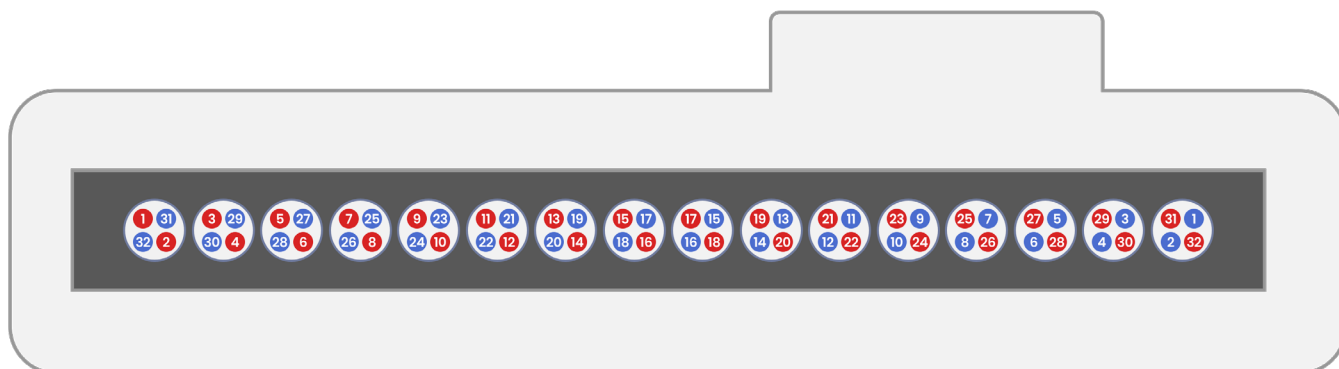


Figure 10 – USConec MMC® 16 - A Pattern - Optical Interface

4.2.2.2 B Pattern

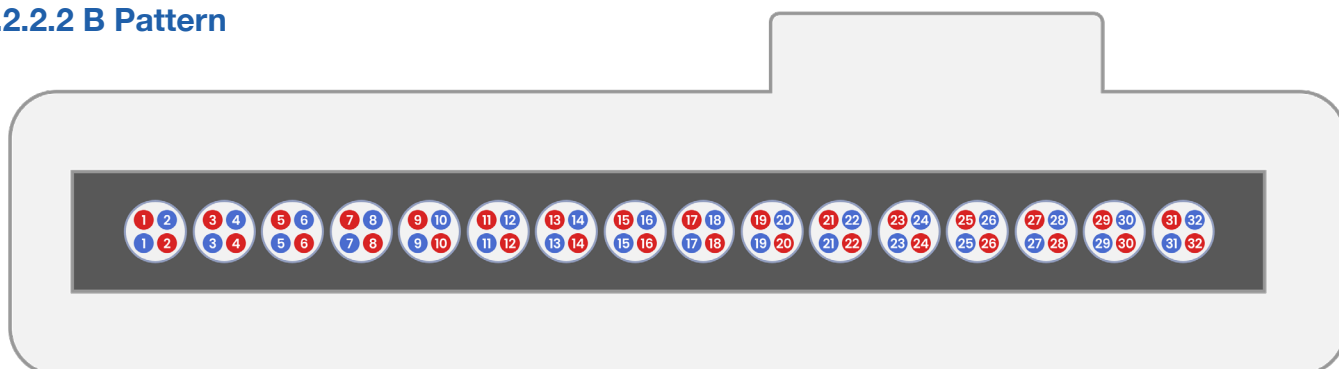


Figure 11 – USConec MMC -16 - B Pattern - Optical Interface

4.2.2.3 C Pattern

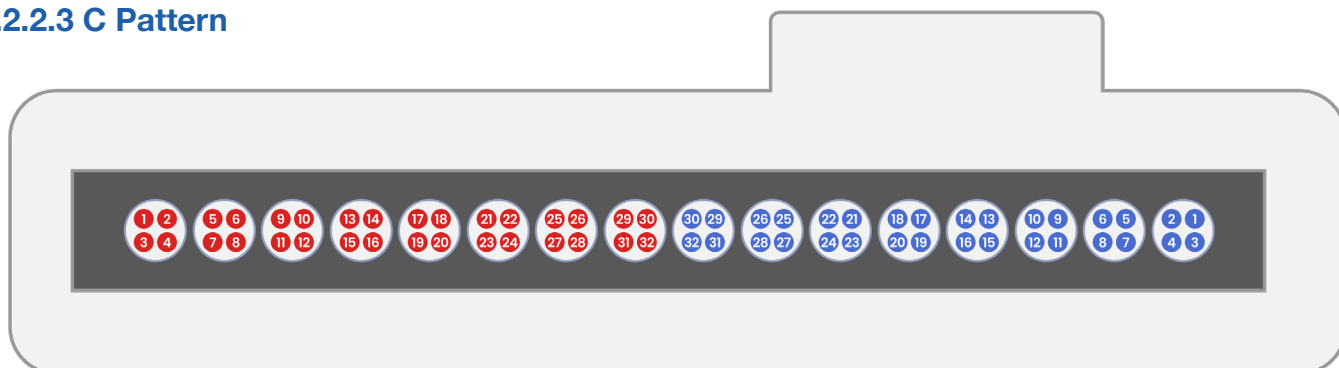


Figure 12 – USConec MMC-16 - C Pattern - Optical Interface

4.2.3 MPO-16 Optical Interface

4.2.3.1 A Pattern

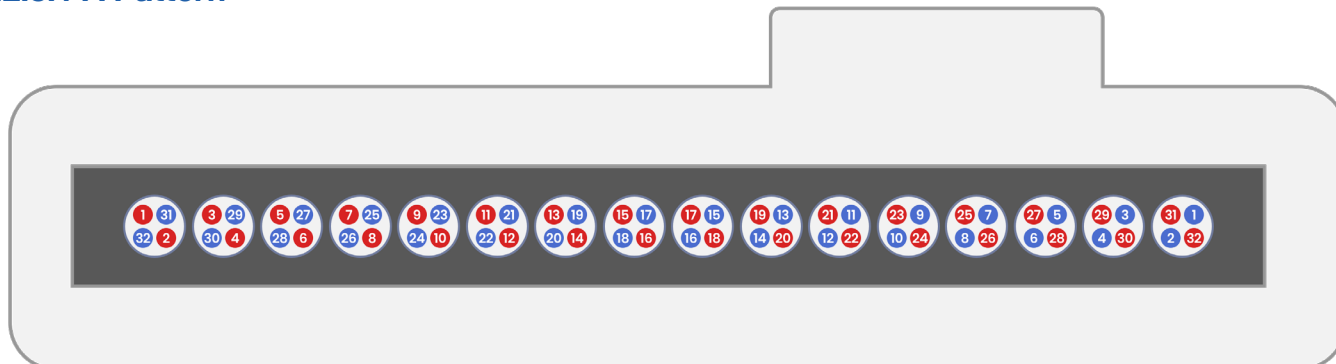


Figure 13 – MPO-16 Optical Interface - A Pattern - Optical Interface

4.2.3.2 B Pattern

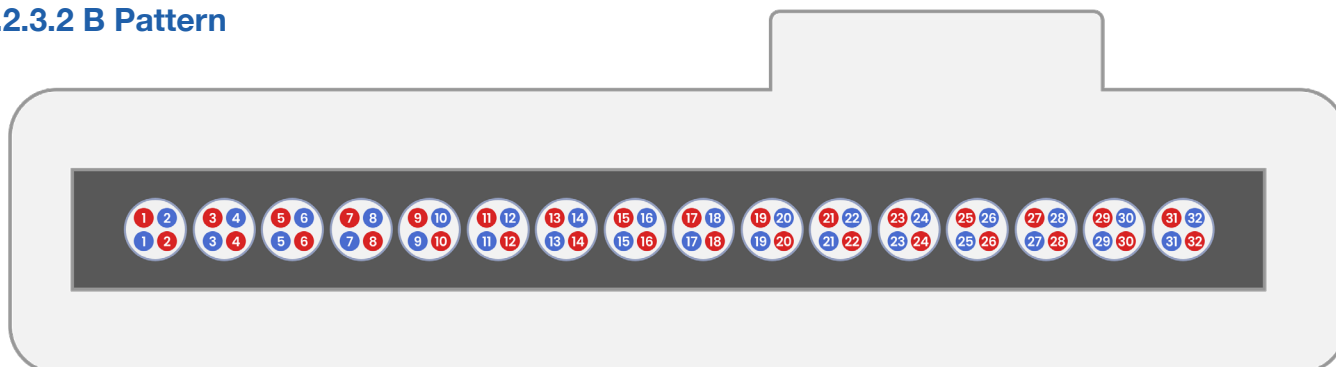


Figure 14 – MPO-16 Optical Interface - B Pattern - Optical Interface

4.2.3.3 C Pattern

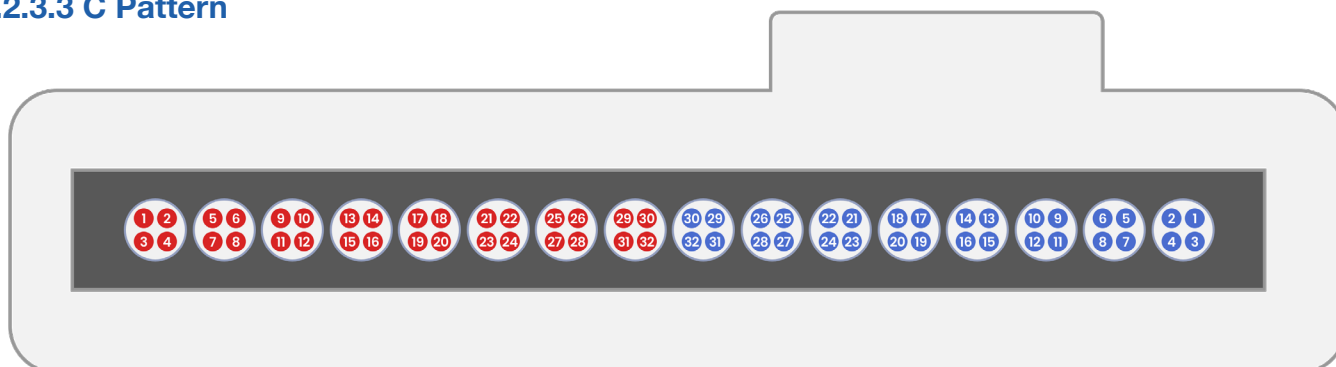


Figure 15 – MPO-16 Optical Interface - C Pattern - Optical Interface

4.3 Dual (Duplex) Multicore (4-MCF) Fiber Connector

Dual fiber optical interfaces are used to directly connect to Multicore Fiber Transceivers or Devices with single ferrule connector interfaces. Typically, dual fiber optical interfaces are used to directly connect two Multicore Fiber Transceivers or CPO Packages (direct connection). Additionally, breakout cables with multi-fiber connectors on one end are broken out, or fanned out, into dual fiber interfaces for connection to equipment in the rack.

4.3.1 Duplex LC Optical Interface

4.3.1.2 A/B Pattern

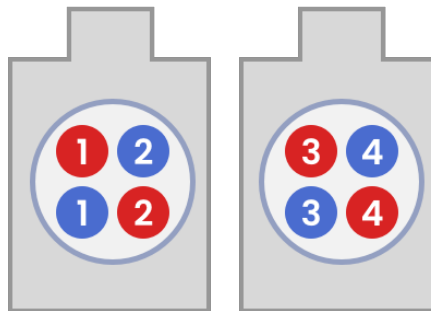


Figure 16 – A/B Pattern

4.3.1.3 C Pattern

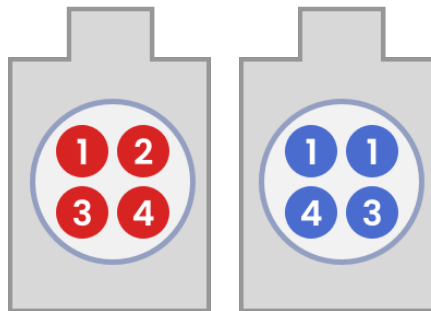


Figure 17 – C Pattern

IEC 61754-20:2012: Fiber optic interconnecting devices and passive components.
Fiber optic connector interfaces – Part 20: Type LC connector family.

4.4 Connector Loss Performance

The table below shows the maximum new product loss of both single fiber connector and multifiber connector terminations on 4-core Multicore Fiber cables based on field trial deployments and end-user loss performance expectations.

Connector Type New Product Performance at Room Temperature	Optical Fiber	Target Maximum Loss (dB)	Notes
Single Fiber Connector (ex. LC, CS, SN, MDC)	4-Core Multi-Core Fiber	0.35 dB	Per mated pair; intrinsic + extrinsic
Multifiber Connector Fiber Connector (ex. MPO, MMC, SN-MT)	4-Core Multi-Core Fiber	0.50 dB	Per mated pair; intrinsic + extrinsic

Table 2 – Connector Loss Budget

NOTE: The table above shows the maximum loss for new product mated connector pairs. System designers shall account for the following additional losses in system designs: (a) Connector repeatability: up to 0.10 dB; (b) Loss change over full operating temperature range: Up to 0.20 dB; and (3) Loss change when connector is subjected to mechanical load: Up to 0.20 dB.

4.5 Fiber Splice

Literature reports that low loss 4-core Multicore fiber splicing can be achieved using advanced splicing equipment with automatic fiber rotation and core recognition image processing, bringing this technology closer to commercial, field-ready deployment.

Feature	Conventional Fiber Splicing	4 Core Multicore Fiber Splicing
Alignment	X, Y, Z Axis (1 Core)	X, Y, Z + Rotation (Multiple Cores)
Typical Loss	0.02 to 0.05 dB	0.10 dB
Maximum Loss	0.10 dB	0.35 dB
Minimum Return Loss	-55 dB	-55 dB

Table 3 – Single-Core vs. Multicore Splicing

References

1. Multicore Fiber Splicing Research - Low-Loss Fusion Splice Techniques, Fitel Furukawa Electric, Aug 24, 2024
2. Loss performance of field-deployed high-density 1152-channel link constructed with 4-core multicore fiber cable, Fujikura, AFL, and Chiral Photonics, OFC 2023 Optica Publishing Group 2023

5.0 Cable Polarity and Proposed Cabling Solutions

Two types of cable polarity are proposed for the multi fiber connector: Straight through and Crossover.

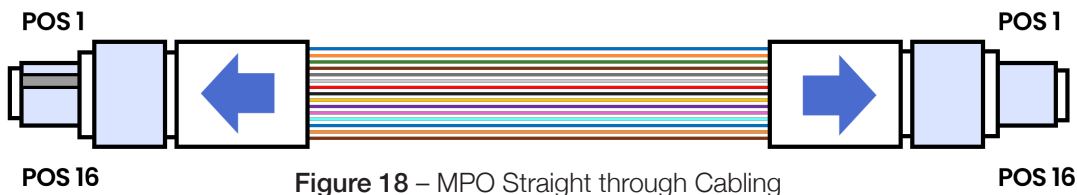
In addition, breakout cabling options are defined by interconnecting one multi fiber connector to multiple fiber connectors.

Ex. 1x Multi fiber connector to 2x Multi fiber connector
Ex. 1x Multi fiber connector to 8x dual fiber connector

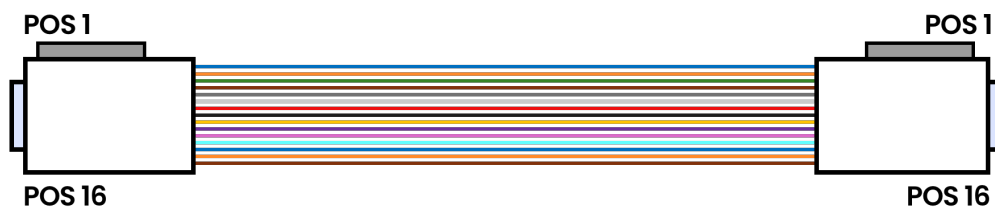
5.1 Straight Through Cabling

Straight through cabling shall be constructed where fiber position 1 goes to fiber position 1.

5.1.1 MPO Straight Through Cabling



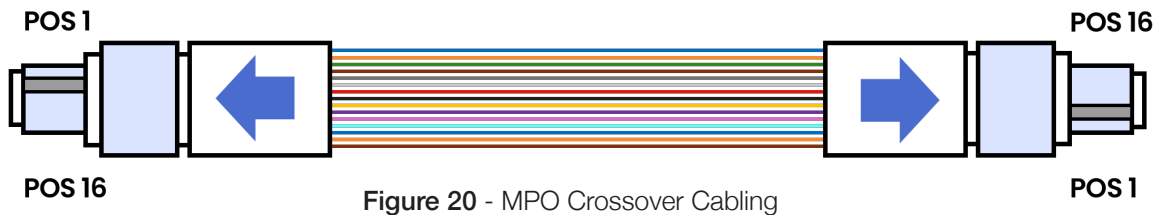
5.1.2 SN-MT and MMC Straight Through Cabling



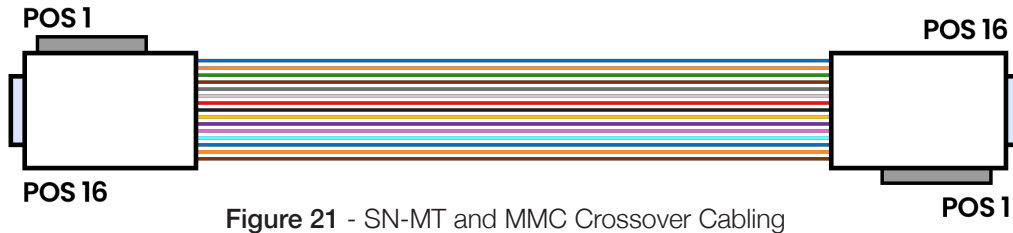
5.2 Crossover Cabling

Crossover cabling shall be constructed where fiber position 1 goes to fiber position 16.

5.2.1 MPO Crossover Cabling



5.2.2 VSFF multi-fiber connector Crossover Cabling

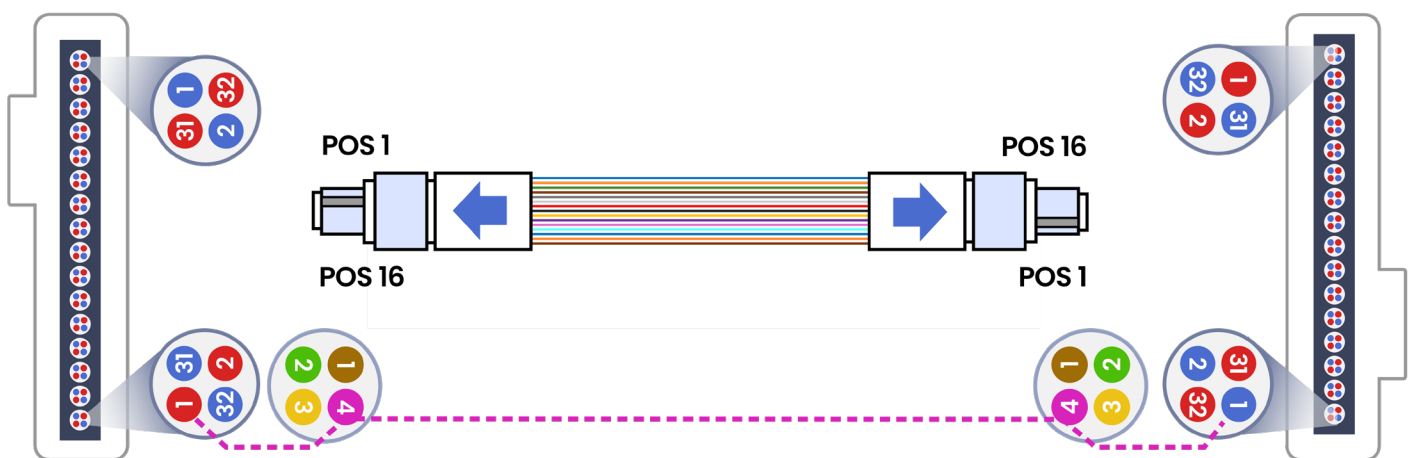


5.3 Connectivity Schemes

This section defines the connectivity schemes for connecting one transceiver or device to another utilizing the device pattern schemes and cable structures.

5.3.1 A-Pattern TRx / Device with Crossover Cable

5.3.1.1 MPO-16 A-Pattern Connection Scheme



5.3.1.2 SN-MT and MMC A-Pattern Connection Scheme

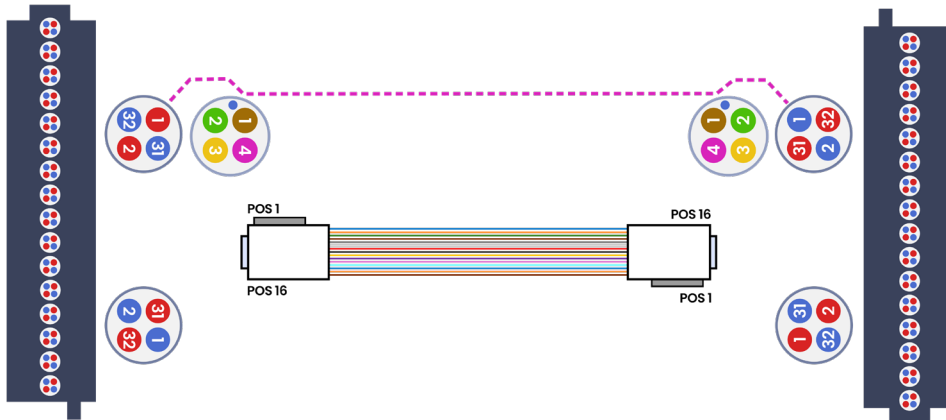


Figure 23 - SN-MT and MMC A-Pattern Connection Scheme

5.3.2 B-Pattern TRx / Device with Straight Through Cable

5.3.2.1 MPO-16 B-Pattern Connection Scheme

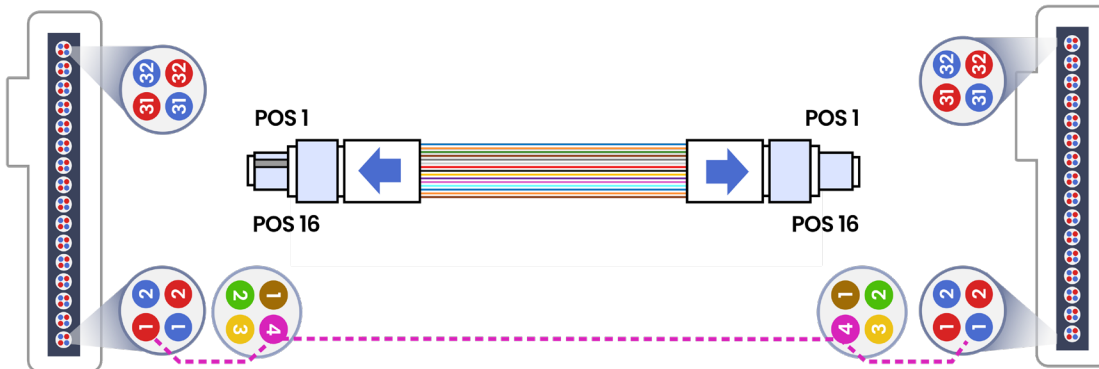


Figure 24 - MPO-16 B-Pattern Connection Scheme

5.3.2.2 SN-MT B-Pattern Connection Scheme

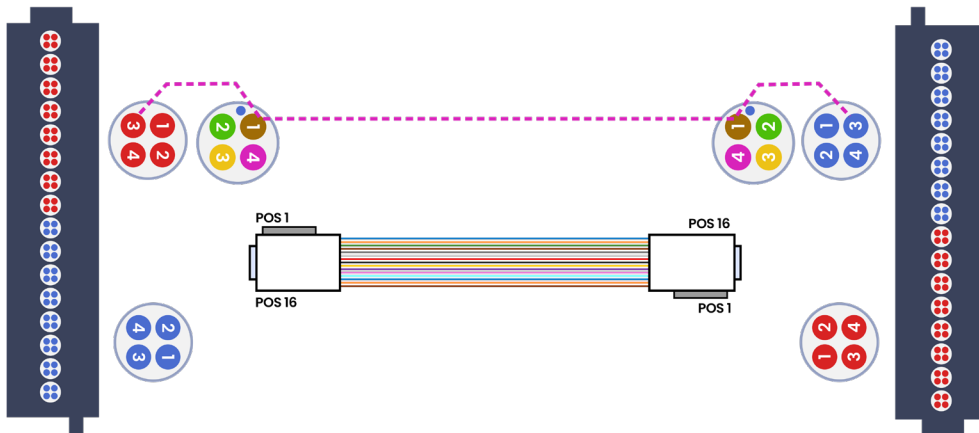


Figure 25 - SN-MT B-Pattern Connection Scheme

5.3.3 C-Pattern TRx / Device with Crossover Cable

5.3.3.1 MPO-16 C-Pattern Connection Scheme

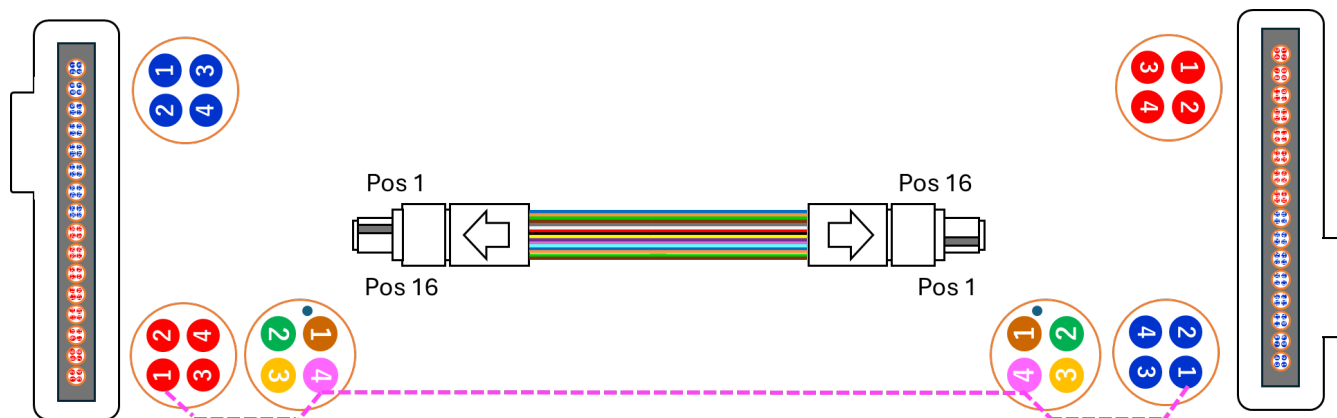


Figure 26 - MPO-16 C-Pattern Connection Scheme

5.3.3.2 SN-MT and MMC™ C-Pattern Connection Scheme

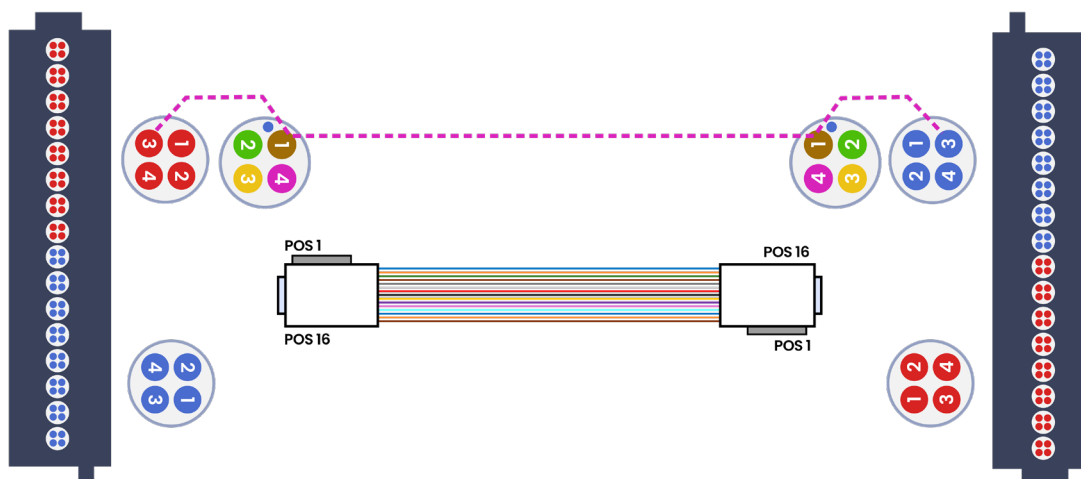


Figure 27 - SN-MT and MMC C-Pattern Connection Scheme

5.4 Breakout Cabling

This section describes the connection schemes of a breakout cabling for A, B and C Patterns

5.4.1 MPO, MMC, SN-MT A Pattern to Dual-LC A Pattern Connection Scheme

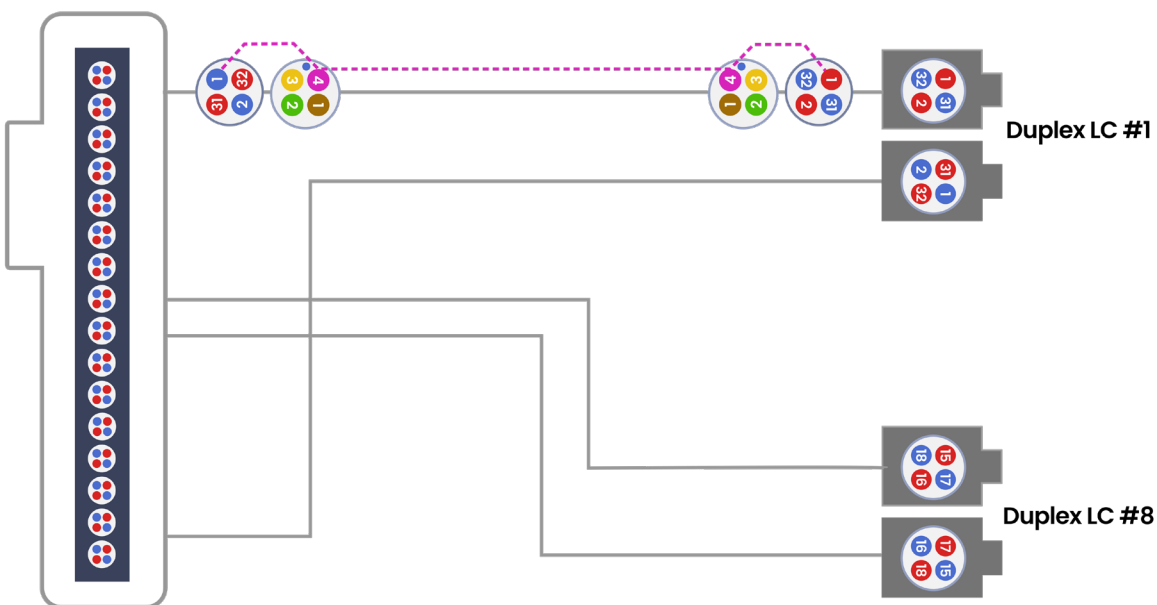


Figure 28 - MPO, MMC, SN-MT A Pattern to Dual-LC A Pattern Connection Scheme

5.4.2 MPO, MMC, SN-MT B Pattern to Dual-LC B Pattern Connection Scheme

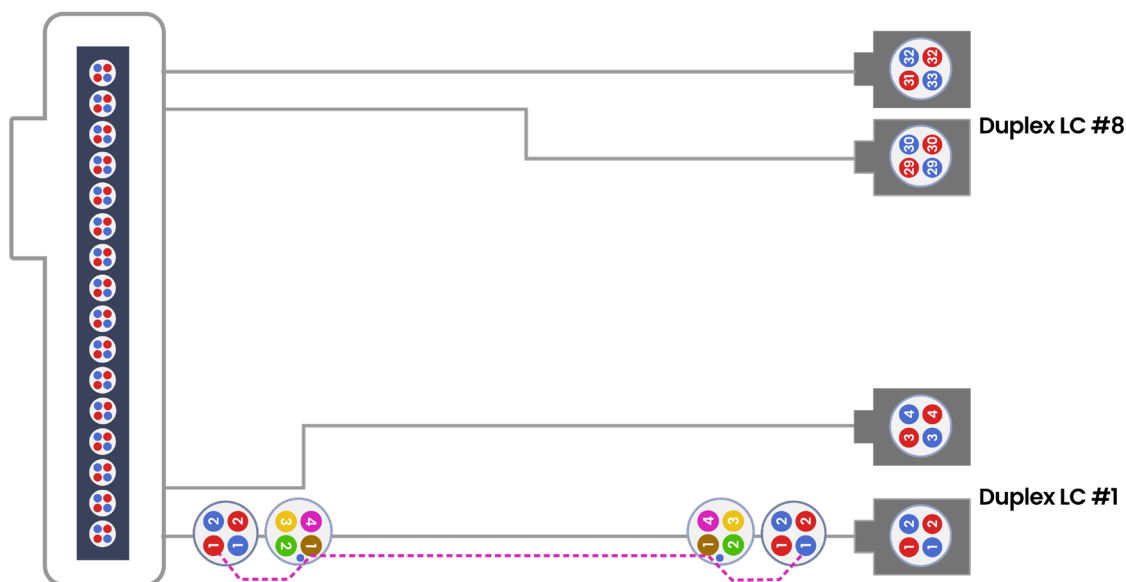


Figure 29 - MPO, MMC, SN-MT B Pattern to Dual-LC B Pattern Connection Scheme

5.4.3 MPO, MMC, SN-MT C Pattern to Dual-LC C Pattern Connection Scheme

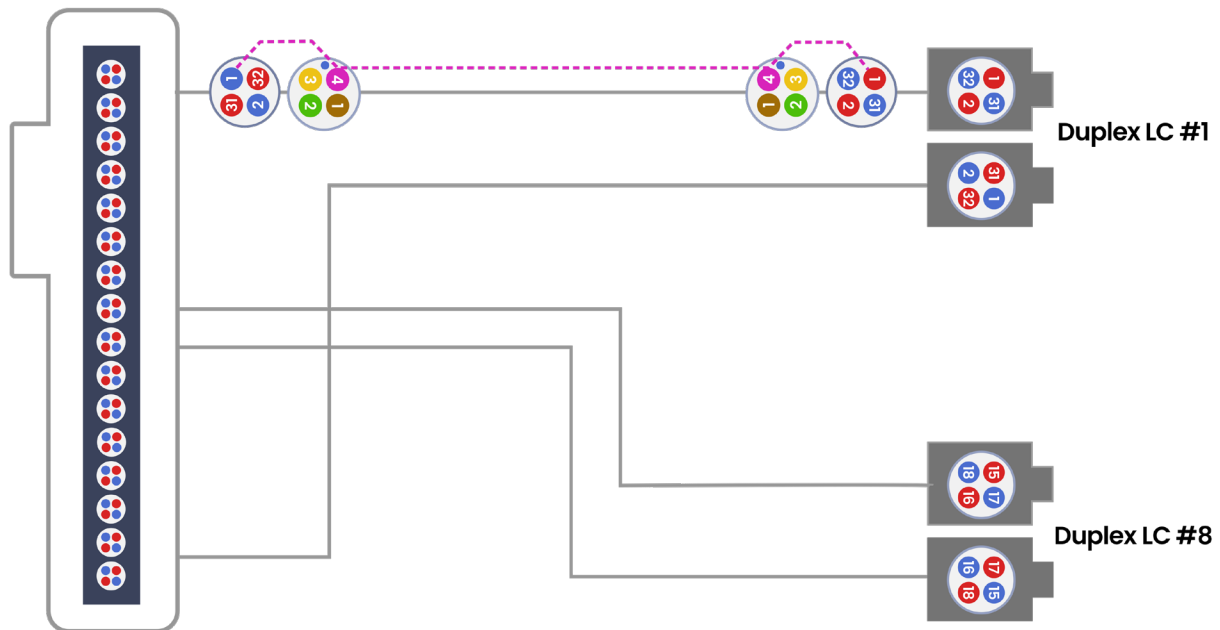


Figure 30 - MPO, MMC, SN-MT C Pattern to Dual-LC C Pattern Connection Scheme

6.0 Fiber Array Unit Specification for PIC Attachment

Scope: This section defines mechanical, optical, and environmental requirements for Fiber Array Units (FAUs) and their interfaces to Photonic Integrated Circuit (PIC) coupling structures in data center applications.

The following subsections establish dimensional tolerances, optical performance limits, and reliability criteria to ensure interoperability between compliant FAU assemblies and PIC interface units sourced from different vendors. All requirements apply at end-of-life (EoL) conditions unless otherwise stated.

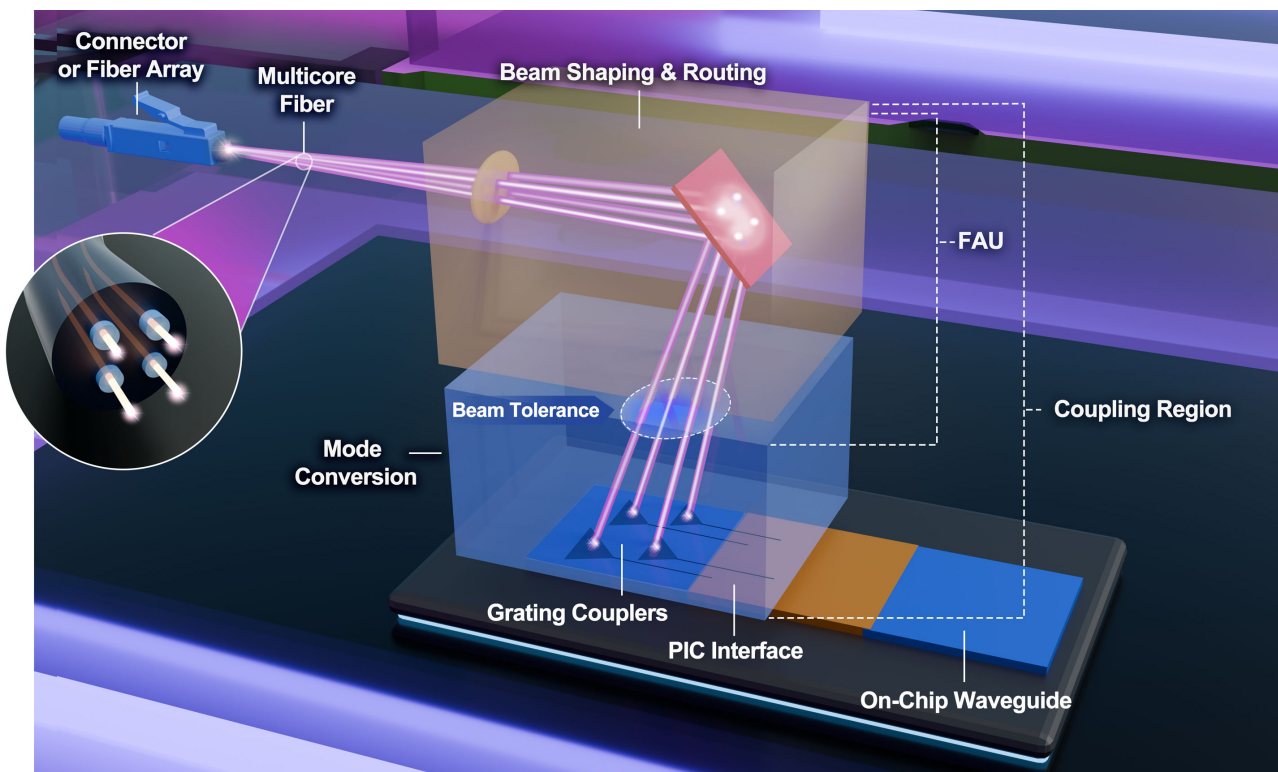


Figure 31 - FAU Interface Rendering



6.1 Fiber Array Unit Introduction

The process of coupling light into and out of photonic integrated circuits (PICs) via optical fibers generally requires several distinct components. These include the fiber(s) and/or fiber array, a fiber attach unit (FAU), a PIC interface unit, and an on-chip coupling building block.

Fibers may be single-mode fibers (SMF), multimode fibers (MMF), hollow-core fibers (HCF), or Multicore fibers (MCF). These fibers can be connected to the FAU either individually or collectively as part of a fiber array.

The FAU can take many forms, but its primary function is to fix the fiber(s) or fiber array in a stationary position with precise alignment relative to the PIC, enabling efficient in- and out-coupling of light with minimal loss. In addition, the FAU is responsible for redirecting and shaping the optical beam toward the optimal direction and profile for connection to the PIC interface unit. This functionality is often realized through assemblies incorporating mirrors and/or lenses for beam redirection and shaping. Some FAUs may also include a fiber-array pitch-reduction capability, allowing for denser optical interconnects to the PIC.

The PIC interface unit comprises the edge region of the chip and may incorporate beam shaping, beam redirection, and fiber-fixing features. It is designed to operate in tandem with the FAU to reduce optical losses and minimize the overall FAU size. This interface often includes lens-shaped surfaces that redirect and shape the beam arriving from a fiber, or that leaving the PIC, to enable coupling from or to the vertical direction. Alternative PIC interface solutions for edge coupling include individual or arrayed V-grooves, which facilitate precise alignment and simple mechanical fixation of fibers relative to the PIC coupling block.

The PIC coupling building block itself is a photonic structure designed to redirect or expand the guided optical mode to improve coupling efficiency with a fiber mode, thereby reducing loss. These structures generally fall into two broad categories: edge-coupling devices and vertical-coupling devices. Edge couplers most commonly consist of inverse-taper waveguides with lengths ranging from approximately 100 μm to 1 mm. To further improve mode matching with the fiber mode, additional design techniques—such as auxiliary waveguides, under-etching, or over-etching—may be employed to tailor the beam shape and enhance overlap between the waveguide and fiber modes.

Vertical coupling devices are typically implemented using grating couplers, which rely on Bragg diffraction to redirect light from the waveguide mode toward a vertically aligned fiber or FAU. These structures consist of periodic arrays of alternating low- and high-refractive-index regions oriented perpendicular to the waveguide propagation direction. Careful tuning of the grating geometry, as well as increased structural complexity through the introduction of two-dimensional grating arrays, can significantly improve mode matching and reduce coupling losses. Such optimizations also enable additional desirable performance metrics, including broadband operation, polarization insensitivity, and polarization diversity.



Both edge-coupling and vertical-coupling approaches offer distinct advantages and disadvantages. Edge coupling typically yields lower insertion losses (often <3 dB), inherently supports polarization-insensitive operation, and provides very broadband performance. However, edge couplers generally occupy more chip area or require additional beam-shaping structures in the FAU or interface unit to improve mode matching with fiber modes.

Furthermore, edge coupling confines optical interconnects to a one-dimensional region along the chip edge. In contrast, vertical grating couplers offer a much smaller footprint and enable a two-dimensional chip surface for optical interconnects without the need for additional beam-shaping elements. They also provide greater design flexibility for implementing polarization- or wavelength-diverse schemes.

Nevertheless, grating couplers typically exhibit higher insertion losses (>5 dB), and simpler designs efficiently couple only TE waveguide modes over a narrower wavelength range compared to edge-coupling solutions. For both approaches, advanced design techniques can mitigate many of these drawbacks, enabling reduced losses, broader bandwidths, and polarization-insensitive or polarization-diverse operation.

6.2 Multicore Fiber Specifics

With respect to Multicore fibers, both edge-coupling and vertical-coupling solutions have been demonstrated or are under active development. Edge-coupling approaches are comparatively less mature, as they require the two-dimensional arrangement of cores at the end of a Multicore fiber to be transformed into a one-dimensional array compatible with edge-coupler geometries. This transformation typically relies on specialized FAUs but does intrinsically allow for beam expansion, which can improve mode matching.

Vertical coupling solutions are generally more practical for Multicore fibers due to their simpler architectural requirements. Conceptually, the primary difference between coupling a single-mode fiber and a Multicore fiber using grating couplers is that the latter requires an array of grating couplers. Given that the core pitch in a typical MCF is approximately $40\text{ }\mu\text{m}$ and the mode-field diameter is on the order of $10\text{ }\mu\text{m}$, arranging grating couplers—each with a footprint of roughly $12\times 12\text{ }\mu\text{m}$ —in a pattern matching the MCF core array is straightforward. This configuration introduces no additional crosstalk, as the grating couplers are larger than the individual core mode fields and sufficiently spaced to prevent evanescent coupling between adjacent structures.

Since grating couplers often require a non-normal fiber incidence angle, the MCF can be aligned accordingly so that light from each core couples efficiently into its corresponding grating coupler. Minor deviations in core angle or position are accommodated by the slightly larger footprint of the grating couplers relative to the core mode-field diameter.

6.3 Rationale for Alignment Tolerances

The FAU shall provide a mechanically stable and optically repeatable interface between the external fiber domain and the PIC interface unit, as defined in Section 8.1 and Figure 1.2. FAU requirements shall be specified so designs are interoperable across suppliers and test results are comparable across laboratories. Misalignment tolerances defined in this section shall ensure compliance with specified optical performance limits, including insertion loss and, where applicable, core-to-core crosstalk for Multicore fiber interfaces.

6.3.1 Mechanical Interface Standards

FAU mechanical interface standards define the physical envelope and positional accuracy requirements at the FAU-to-PIC interface unit mating surface. Reference coordinates shall be established at the FAU output face, with the Z-axis coincident with the optical axis of Core 1 (or the single fiber for single-channel FAUs) and the X–Y plane perpendicular to Z.

- Fiber type compatibility: FAUs shall be specified for use with one or more of the following fiber types:
 - Single-Mode Fiber (SMF) — per IEC 60793-2-50 and ITU-T G.652
 - Polarization-Maintaining Fiber (PMF) — per IEC 60793-2-30
 - Multi-Mode Fiber (MMF) — per IEC 60793-2-10 (OM3, OM4, OM5)
 - Hollow-Core Fiber (HCF) — per applicable manufacturer specification
 - Multicore Fiber (MCF) — per Section 9.0 of this document
- Reference coordinate system: The FAU shall define and document a reference coordinate origin and axis orientation at the mating interface. The coordinate specification shall include X–Y lateral origin (typically Core 1 center or geometric array center), Z-axis orientation, and keying or fiducial reference for rotational alignment.
- Misalignment tolerances at the FAU–PIC interface plane:
 - Lateral ($\Delta x, \Delta y$): Maximum $\pm 0.5 \mu\text{m}$ from nominal core position
 - Axial (Δz): Maximum $\pm 5 \mu\text{m}$ along the optical axis
 - Angular ($\Delta \theta$): Maximum $\pm 0.3^\circ$ tip and tilt combined

Parameter	Symbol	Min	Max	Notes
Compatible Fiber Types	—	—	—	SMF, PMF, MMF, HCF, MCF
Lateral Misalignment Tolerance	$\Delta x, \Delta y$	—	$\pm 0.5 \mu\text{m}$	At PIC interface plane
Axial Misalignment Tolerance	Δz	—	$\pm 5 \mu\text{m}$	Along optical axis
Angular Misalignment Tolerance	$\Delta \theta$	—	$\pm 0.3^\circ$	Tip and tilt combined
Reference Coordinate Origin	—	—	—	Defined at FAU–PIC mating surface; see §8.3 coordinate specification
Pitch Accuracy (MCF FAU)	p	—	$\pm 0.3 \mu\text{m}$	Core-to-core pitch at output face

Table 4 — FAU Mechanical Interface Requirements

6.3.2 Optical Coupling Fundamentals

Optical coupling between an optical fiber and a photonic integrated circuit (PIC) is governed by the overlap of their respective optical modes. For single-mode fibers and typical PIC waveguides, the optical mode may be approximated as Gaussian.

The coupling efficiency under lateral misalignment is given by:

$$\eta = \exp \left(-\frac{2(\Delta x^2 + \Delta y^2)}{w^2} \right)$$

where:

- η is the coupling efficiency,
- $\Delta x, \Delta y$ are lateral offsets, and
- w is the mode field radius (typically $\approx 5 \mu\text{m}$ for a $10 \mu\text{m}$ mode field diameter).

The corresponding insertion loss is:

$$\text{Loss (dB)} = -10 \log_{10}(\eta)$$

Typical loss values as a function of lateral offset are summarized in Table 5.

Lateral Offset	Typical Loss
0.5 μm	~ 0.1 dB
1.0 μm	~ 0.3 – 0.5 dB
2.0 μm	≥ 1 dB

Table 5 — Lateral Misalignment vs. Insertion Loss

These results support a target lateral alignment tolerance of $\pm 1 \mu\text{m}$ and a maximum tolerance of $\pm 1.5 \mu\text{m}$.

6.3.3 Axial Misalignment

Axial misalignment (Δz) affects coupling efficiency due to beam divergence. The relevant scale is the Rayleigh range, which is typically on the order of 30–50 μm for standard single-mode fibers.

Within a range of $\pm 5 \mu\text{m}$ to $\pm 10 \mu\text{m}$:

- The additional insertion loss is typically less than 0.5 dB.

Beyond this range:

- Mode mismatch increases rapidly, resulting in significant coupling degradation.

Accordingly, the following limits are specified:

- Target: $\pm 5 \mu\text{m}$
- Maximum: $\pm 10 \mu\text{m}$

6.3.4 Angular Misalignment

Angular misalignment ($\Delta\theta_x, \Delta\theta_y$) impacts coupling efficiency depending on the coupling mechanism.

Grating couplers exhibit strong angular sensitivity, with an effective acceptance window typically on the order of ± 1 – 2° . Edge coupling is generally less sensitive but remains affected by angular deviation.

Typical behavior includes:

- $\sim 0.5^\circ$: minor insertion loss penalty
- $\sim 1.0^\circ$: noticeable degradation

The following limits are therefore defined:

- Target: $\pm 0.5^\circ$
- Maximum: $\pm 1.0^\circ$

6.3.5 Multicore Fiber Considerations

In multicore fiber (MCF) systems, alignment must be achieved simultaneously across all cores. This introduces additional constraints beyond single-fiber coupling.

For a representative MCF geometry:

- Core pitch: ~40 μm
- Radial distance from fiber center: ~20 μm

6.3.5.1 Rotational Misalignment

Rotational misalignment ($\Delta\theta_z$) introduces lateral displacement of individual cores according to:

$$\Delta r \approx r \cdot \theta$$

where:

- r is the radial distance from the fiber center, and
- θ is the rotation angle (in radians).

For $r \approx 20 \mu\text{m}$, the induced displacement is:

Rotation	Induced Lateral Shift
0.5°	~0.17 μm
1.0°	~0.35 μm

Table 6 — Induced Lateral Shift

Although small in magnitude, this displacement:

- Adds to existing lateral offsets,
- Varies across cores, and
- Introduces channel-dependent insertion loss variation.

Accordingly, rotational alignment must be more tightly controlled than lateral alignment.

The following limits are specified:

- Target: $\pm 0.2^\circ$
- Maximum: $\pm 0.5^\circ$

6.3.5.2 Crosstalk Sensitivity

Intrinsic crosstalk in Multicore fiber is typically specified as ≤ -40 dB over 1 km. Misalignment can increase coupling between adjacent cores by altering modal overlap.

To preserve system performance, the allowable additional crosstalk penalty due to misalignment shall not exceed approximately 3 dB relative to the intrinsic specification.

This requirement imposes constraints on:

- Lateral alignment accuracy, and
- Rotational alignment stability.

6.3.6 Manufacturing Considerations

Specified tolerances shall be achievable using established FAU assembly processes.

Typical capabilities include:

- Active alignment:
 - Lateral accuracy: ± 0.5 – 1.0 μm
 - Angular accuracy: sub-degree
- Passive alignment (e.g., V-groove with fiducials):
 - Lateral accuracy: ± 1 – 2 μm
 - Rotational accuracy: $\sim 0.5^\circ$ – 1°

Tolerance values defined in this specification are selected to ensure compatibility with these manufacturing capabilities while maintaining acceptable optical performance.

6.3.7 Summary of Tolerance Limits

Final tolerance values represent a balance between optical physics, Multicore system requirements, and manufacturability.

Parameter	Physics Limit	Manufacturing Capability	Specified Range
$\Delta x, \Delta y$	< 1 μm ideal	~ 1 – 2 μm	1 – 1.5 μm
Δz	< 5 μm ideal	~ 5 – 15 μm	5 – 10 μm
$\Delta \theta_x, \Delta \theta_y$	$< 0.5^\circ$ ideal	~ 0.5 – 1°	0.5 – 1°
$\Delta \theta_z$	tighter (MCF)	~ 0.2 – 0.5°	0.2 – 0.5°

Table 7 — Alignment Tolerance Summary

The Figure (below) shows a 4-core alignment error study across three mechanical misalignment cases. This is a first-order case study using just lateral shift and in-plane rotation. Each panel is a top-down view of the core positions in (x) and (y) in micrometers.

Symbol descriptions:

- The four points at the corners represent the four cores in the array.
- The small offset between the two marker sets shows misregistration between the two coupled interfaces.
- (dx) is a lateral shift in (x).
- (θ) is a small rotational misalignment.

Multicore Lateral Shift + Rotation Case Study

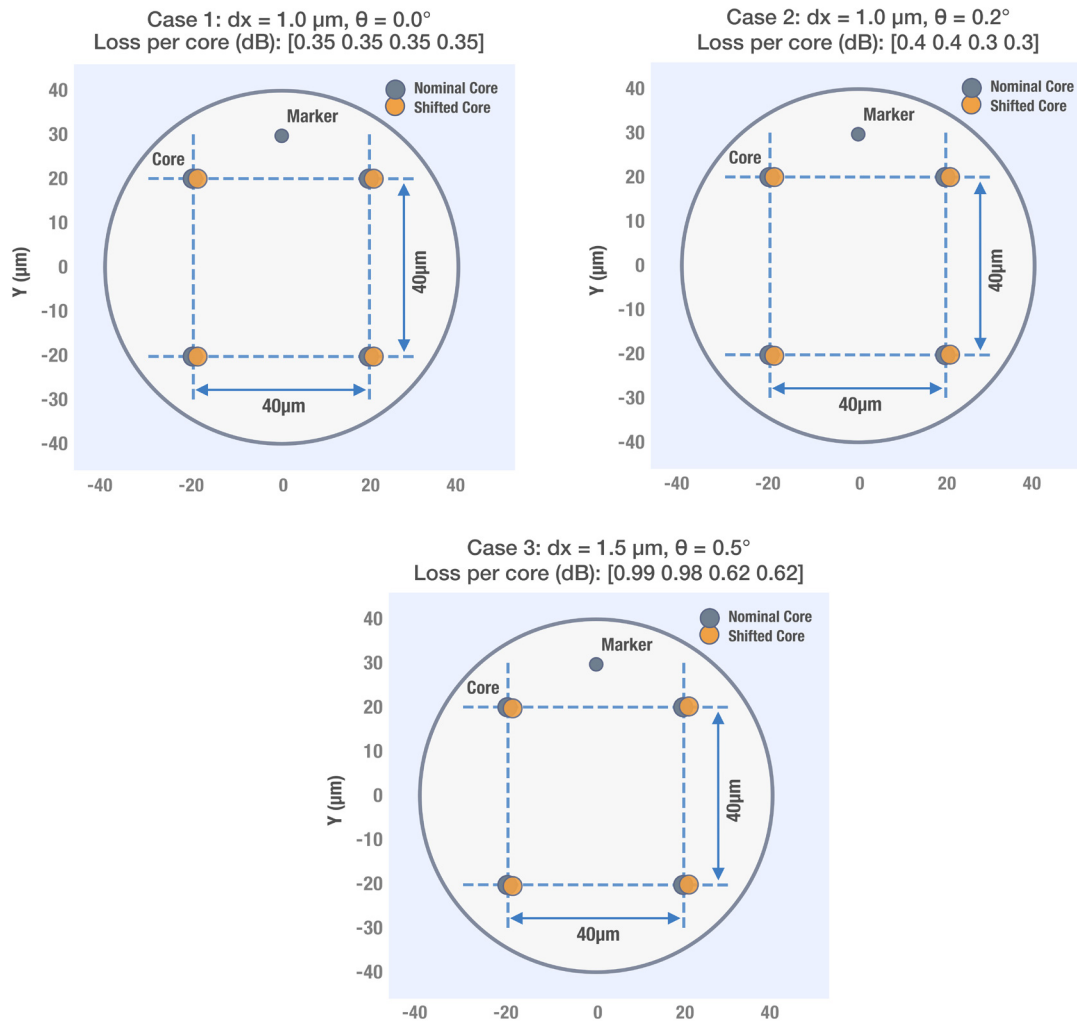


Figure 32 — 4-Core Alignment Error Study Across Three Misalignment Cases



What each case is showing:

- Case 1: ($dx = 1.0 \mu\text{m}$), ($\theta = 0^\circ$)

A pure lateral shift. All four cores see the same loss, about (0.35) dB each, because the displacement is uniform and symmetric.

- Case 2: ($dx = 1.0 \mu\text{m}$), ($\theta = 0.2^\circ$)

Now a small rotation is added. The loss is no longer perfectly uniform: two cores are at about (0.4) dB and two at about (0.3) dB. The rotation helps some cores slightly and hurts others slightly.

- Case 3: ($dx = 1.5 \mu\text{m}$), ($\theta = 0.5^\circ$)

Both the lateral shift and the rotation are larger. Loss rises substantially and becomes more uneven: about (0.99), (0.98), (0.62), and (0.62) dB. That means the misalignment is now large enough that different cores experience materially different coupling quality.

The main takeaways:

- Pure translation tends to produce uniform degradation across cores.
- Adding rotation introduces core-to-core imbalance.
- As both translation and rotation increase, total loss increases and channel uniformity gets worse.

6.3.8 System-Level Considerations

The alignment tolerances and optical performance limits defined in this section are intended to ensure:

- Acceptable insertion loss across all active optical channels.
- Minimal channel-to-channel performance variation.
- Crosstalk performance consistent with high-density parallel optical interfaces.
- Manufacturable and repeatable FAU-to-PIC assembly processes.

The normative target application is a 4-core single-mode Multicore fiber (MCF) interface.

6.3.8.1 Fiber Compatibility

The baseline interface defined in this specification shall support:

- 4-core single-mode Multicore fiber (MCF)
- Nominal core pitch: 40 μm

Each core shall operate in single-mode over the specified operating wavelength range.

The following fiber implementations may additionally be supported on an implementation-specific basis:

- Single-mode fiber (SMF)
- Polarization-maintaining fiber (PMF)
- Multi-mode fiber (MMF)
- Hollow-core fiber (HCF)

Implementations using non-MCF interfaces shall require independent validation of:

- Insertion loss
- Return loss
- Channel variation
- Crosstalk performance

6.3.8.2 Reference Coordinate System

A common right-handed coordinate system shall be used for all FAU and PIC alignment specifications.

The coordinate system shall be defined as follows:

Parameter	Definition
x	Lateral horizontal axis in coupling plane
y	Lateral vertical axis in coupling plane
z	Axial direction normal to PIC interface plane

Table 8 — Coordinate System

Rotational axes shall follow the right-hand rule:

Rotation	Definition
θ_x	Rotation about x-axis (tip)
θ_y	Rotation about y-axis (tilt)
θ_z	Rotation about z-axis (roll/yaw)

Table 9 — Rotational Axes

The coordinate origin shall be defined at the nominal center of the 4-core optical interface.
The following measurement reference planes shall be identified in all compliance reports:

Reference Plane	Description
TP0	PIC optical interface plane
TP1	FAU optical output plane
TP2	External connector reference plane

Table 10 — Measurements Reference Planes

6.3.8.3 Mechanical Alignment Tolerances

Parameter	Target	Maximum
Δx	$\pm 1.0 \mu\text{m}$	$\pm 1.5 \mu\text{m}$
Δy	$\pm 1.0 \mu\text{m}$	$\pm 1.5 \mu\text{m}$

Table 11 — Lateral Misalignment

Parameter	Target	Maximum
Δz	$\pm 5 \mu\text{m}$	$\pm 10 \mu\text{m}$

Table 12 — Axial Misalignment

Parameter	Description	Target	Maximum
θx	Tip	$\pm 0.5^\circ$	$\pm 1.0^\circ$
θy	Tilt	$\pm 0.5^\circ$	$\pm 1.0^\circ$
θz	Roll/Yaw (MCF critical)	$\pm 0.2^\circ$	$\pm 0.5^\circ$

Table 13 — Angular Misalignment

Combined alignment error may alternatively be evaluated using a normalized budget function:

$$B = \left(\frac{\Delta x}{1.5}\right)^2 + \left(\frac{\Delta y}{1.5}\right)^2 + \left(\frac{\Delta z}{10}\right)^2 + \left(\frac{\theta_x}{1.0}\right)^2 + \left(\frac{\theta_y}{1.0}\right)^2 + \left(\frac{\theta_z}{0.5}\right)^2$$

where:

- translational units are in μm
- angular units are in degrees

Compliance criterion: $B \leq 1.0$

6.3.8.4 Insertion Loss

Per-core insertion loss shall satisfy:

Interface Type	Target	Maximum
Edge-coupled	≤ 1.5 dB	≤ 3.0 dB
Grating-coupled	≤ 4.0 dB	≤ 7.0 dB

Table 14 — Lateral Misalignment

Additional requirements:

Parameter	Requirement
Mean IL across active cores	≤ 2.2 dB (edge-coupled target)
Channel-to-channel IL variation	≤ 0.5 dB

Table 15 — Insertion Loss Requirements

6.3.8.5 Return Loss

Return loss measured at TP1 shall satisfy:

Parameter	Requirement
Mean IL across active cores	≤ 2.2 dB (edge-coupled target)
Channel-to-channel IL variation	≤ 0.5 dB

Table 16 — Return Loss

Measurements shall be performed across the specified operating wavelength and temperature range.

6.3.8.6 Mode Overlap Efficiency

Optical coupling efficiency between the FAU output mode and PIC acceptance mode shall satisfy:

Parameter	Requirement
Minimum overlap efficiency	$\geq 85\%$
Recommended target	$\geq 90\%$

Table 17 — Mode Overlap Efficiency

Equivalent overlap-induced coupling penalty:

Parameter	Requirement
Target penalty	≤ 0.46 dB
Maximum penalty	≤ 0.7 dB

Table 18 — Mode Overlap Penalties

Mode overlap calculations shall use Gaussian mode approximation unless otherwise specified.

6.3.9 Numerical Aperture and Beam Divergence

For single-mode per-core operation:

Parameter	Requirement
Effective numerical aperture	0.11 ± 0.02
Far-field half-angle divergence	6° – 9°

Table 19 — Numerical Aperture and Beam Divergence

All NA and divergence measurements shall specify:

- Wavelength
- Polarization condition
- Measurement method
- Reference plane

6.4 Optical Performance Requirements

Optical performance shall be characterized under conditions representative of the nominal operating point ($23\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$, fiber mated to compliant PIC interface unit, no applied stress). Measurements shall be performed using calibrated equipment traceable to national metrology standards.

- **Insertion loss (IL):** Maximum per-channel insertion loss inclusive of all coupling losses within the FAU subassembly, from fiber input to FAU output face.
- **Return loss / reflection loss (RL):** Minimum back-reflection suppression at the FAU output face. Angle-polished (APC) end-faces or equivalent anti-reflection treatment are required for $\text{RL} \geq 55\text{ dB}$.
- **Beam shape:** Gaussian mode overlap efficiency shall be characterized at (a) the fiber surface and (b) the PIC interface unit input aperture. Mode field diameter (MFD) shall be matched to the target fiber specification within $\pm 10\%$.
- **Beam numerical aperture / divergence:** Output beam NA or half-angle divergence ($1/e^2$) shall be documented and shall not exceed the nominal fiber NA by more than ± 0.01 .

Parameter	Symbol	Min	Max	Notes
Insertion Loss (per channel)	IL	—	0.5 dB	Includes fiber-to-FAU coupling
Return / Reflection Loss	RL	55 dB	—	Angle-polished or APC end-face
Gaussian Mode Overlap (fiber surface)	η_f	90 %	—	MFD matched to fiber specification
Gaussian Mode Overlap (interface unit)	η_i	85 %	—	At PIC coupler input aperture
Numerical Aperture (output beam)	NA	—	Fiber NA ± 0.01	Per fiber type specification
Beam Divergence (half-angle, $1/e^2$)	θ_d	—	Per fiber NA	Measured at FAU exit face

Table 20 — FAU Optical Performance Requirements

- Use with type of fiber (SMF, PMF, MMF, HCF, MCF)
- Reference coordinates between FAU and PIC interface unit



6.4.1 Optical Performance Requirements

- Insertion loss (dB)
- Reflection loss (dB)
- Beam shape at fiber surface and interface unit (i.e. Gaussian mode overlap percentage)
- Beam numerical aperture or divergence

6.4.2 PIC Interface Unit Standards

The PIC Interface Unit (PIU) is the passive optical subassembly that mediates coupling between the FAU and the on-chip PIC coupling building block (edge coupler or grating coupler). The PIU may include microlenses, spot-size converters, prism arrays, or precision spacers. Requirements below apply to the PIU in isolation (intrinsic performance) unless otherwise noted.

Mechanical Interface Standards

The PIU shall be designed to accept compliant FAU assemblies as defined in §8.3 and interface to the PIC surface or edge per the parameters below. All dimensional specifications refer to the as-assembled state at $23\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$.

- **Fiber type and FAU compatibility:** The PIU shall specify and document compatible fiber types and FAU configurations.
- **Height above chip surface (h_{chip}):** Measured from the chip active waveguide layer to the FAU mating face of the PIU. Tolerance on h_{chip} shall be $\pm 2\text{ }\mu\text{m}$.
- **Height above chip edge (h_{edge}):** For edge-coupled configurations, measured from the chip cleaved or diced edge. Tolerance $\pm 2\text{ }\mu\text{m}$.
- **FAU attachment distance (d_{att}):** Nominal gap at the mating face between FAU exit face and PIU input aperture. Value and tolerance shall be documented per design.
- **Alignment fiducial marks:** A minimum of two (2) fiducial marks shall be provided on the PIU body or mounting substrate. Fiducial position accuracy shall be $\pm 0.5\text{ }\mu\text{m}$ relative to the optical axis array center. Fiducial geometry shall comply with the format defined in the supplementary Fiducial Specification (Annex B).
- **Misalignment tolerances:**
 - Lateral ($\Delta x, \Delta y$): $\pm 0.5\text{ }\mu\text{m}$ at the chip coupler input
 - Axial (Δz): $\pm 5\text{ }\mu\text{m}$ along the optical axis
 - Angular ($\Delta \theta$): $\pm 0.3^{\circ}$ tip and tilt combined

Parameter	Symbol	Min	Max	Notes
Compatible Fiber / FAU Types	—	—	—	SMF, PMF, MMF, HCF, MCF FAUs
Height Above Chip Surface	h_{chip}	—	TBD μm	Measured from chip active layer
Height Above Chip Edge	h_{edge}	—	TBD μm	For edge-coupled configurations
FAU Attachment Distance	d_{att}	—	TBD μm	Nominal gap at mating face
Alignment Fiducial Marks see §8.5 fiducial spec	—	—	—	≥ 2 marks; position accuracy $\pm 0.5 \mu\text{m}$;
Lateral Misalignment Tolerance	$\Delta x, \Delta y$	—	$\pm 0.5 \mu\text{m}$	At chip coupler input
Axial Misalignment Tolerance	Δz	—	$\pm 5 \mu\text{m}$	Along optical axis
Angular Misalignment Tolerance	$\Delta\theta$	—	$\pm 0.3^\circ$	Tip and tilt combined

Table 21 — PIC Interface Unit Mechanical Requirements

6.4.3 Optical Performance Requirements

PIU optical performance shall be measured in the as-assembled condition with the FAU mated per §8.3. Insertion loss values are intrinsic to the PIU and do not include the FAU contribution.

- **Insertion loss:** Per-channel passive coupling loss through the PIU, measured from FAU mating face to PIC coupler input.
- **Return / reflection loss:** Back-reflection from the PIU into the FAU, minimized by anti-reflection coatings or angled interfaces.
- **Beam shape (Gaussian mode overlap):** Mode overlap between PIU output beam and PIC waveguide mode, calculated from measured near-field beam profiles.
- **Numerical aperture / divergence:** Output beam NA or half-angle divergence at the PIC coupler input aperture, documented per coupler type.

Parameter	Symbol	Min	Max	Notes
Insertion Loss (per channel)	IL	—	0.5 dB	Intrinsic coupler loss, passive
Return / Reflection Loss	RL	40 dB	—	At fiber-to-PIC interface
Gaussian Mode Overlap	η	90 %	—	Mode-matched to PIC waveguide mode
Numerical Aperture / Divergence	NA	—	Per coupler type	Edge or grating coupler spec applies

Table 22 — PIC Interface Optical Performance Requirements

6.5 Interface Loss Budget – Fiber to PIC

Purpose: This section provides loss allocation guidelines for each interface element in the fiber-to-PIC optical path, enabling FAU designers and system integrators to construct and validate end-to-end link budgets.

The following figure and table identify the discrete interface boundaries and their associated maximum per-interface loss contributions. Loss values represent the maximum allowed intrinsic loss of the specific part or interface at end-of-life, under nominal operating conditions ($23\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$, no applied stress). System margin for environmental drift, aging, and connector repeatability shall be allocated separately by the system designer.

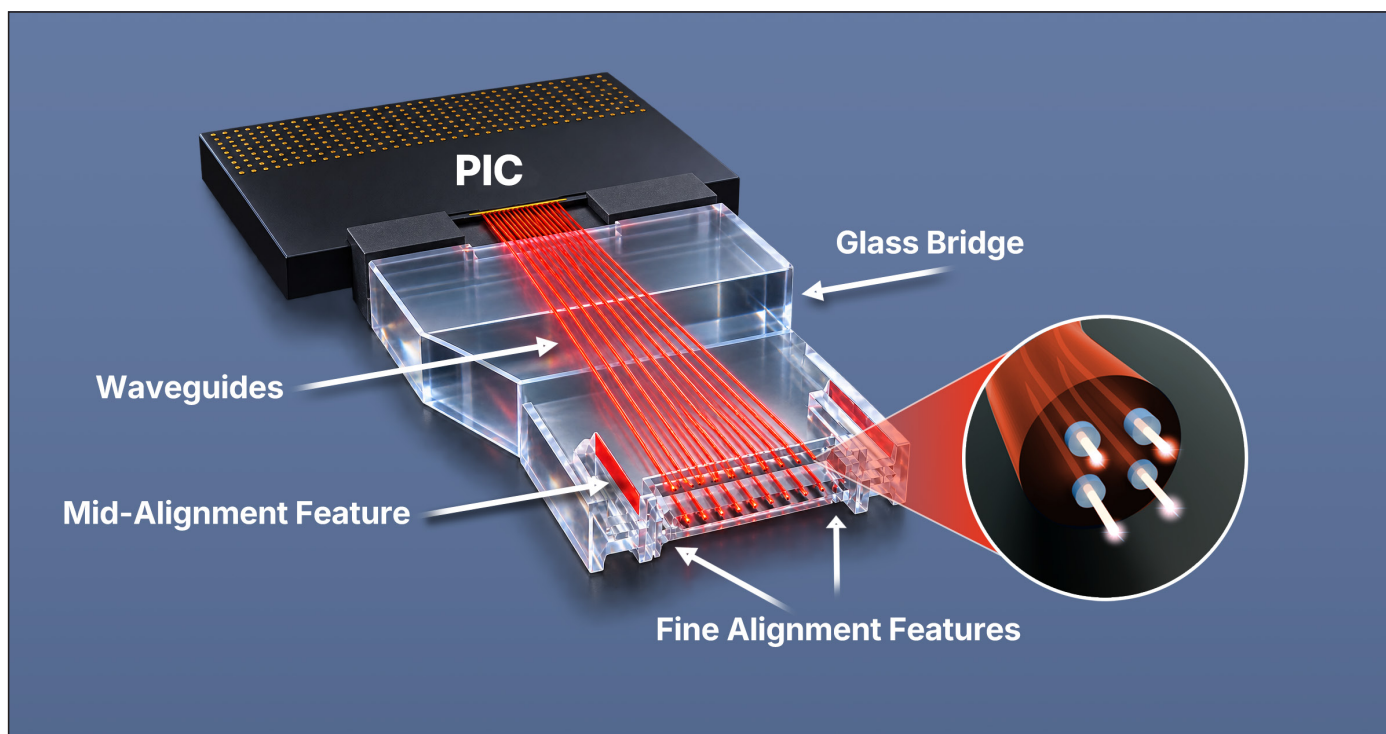


Figure 33 — Fiber-to-PIC Interface

6.5.1 Per-Interface Loss Definitions and Limits

Loss at each interface is defined as the ratio of optical power at the interface input to optical power at the interface output, expressed in dB. Intrinsic loss refers to the theoretical minimum loss achievable with perfect alignment; it excludes connector repeatability, contamination, and extrinsic alignment losses, which shall be budgeted separately.

Interface Element	Component Type	Max Loss (dB)	Notes
4-Core MCF Connector (Single fiber connector and Multifiber connector)	Fiber connector (MCF)	0.35 dB	Per mated pair; intrinsic + extrinsic
4-Core MCF Connector (Multifiber connector)	Fiber connector (MCF)	0.5 dB	Per mated pair; intrinsic + extrinsic
FAU Internal (fiber-to-collimator)	FAU subassembly	0.20 dB	Per channel
FAU-to-PIC Interface Unit	Passive coupling gap	0.30 dB	Air-gap or index-match gel
Edge Coupler (SMF input)	PIC building block	1.00 dB	At center wavelength
Grating Coupler (SMF input)	PIC building block	2.00 dB	At center wavelength, optimal θ

Table 23 — Interface Loss Budget: Maximum per Interface Intrinsic Loss Allocations

NOTE: System designers shall add the following additional loss margins to the intrinsic values above: (a) Connector repeatability: +0.1 dB per mated pair; (b) Environmental drift allowance: +0.2 dB per FAU–PIU interface; (c) Contamination allowance: +0.1 dB per connector. A total link margin of at minimum 1.0 dB is recommended for production data center deployments.

6.5.2 Loss Stack Example

The following example illustrates a representative worst-case loss stack for a 4-core MCF link from fiber patch panel to PIC waveguide input, using components at their maximum specified loss:

Interface Element	Component	Max (dB)	Cumulative (dB)
4-Core MCF Mated Connector Pair	Fiber connector	0.35	0.35
FAU Internal (per channel)	FAU subassembly	0.20	0.55
FAU-to-PIU Coupling	Passive gap	0.30	0.85
PIC Interface Unit (passive)	PIU	0.50	1.35
Edge Coupler (SMF-equivalent)	PIC building block	1.00	2.35
Total Intrinsic (worst-case)	—	—	2.35

Table 24 — Example Loss Stack: 4-core MCF to PIC Coupler (Worst Case)

NOTE: A cumulative intrinsic loss of 2.35 dB (2.5 dB with Multifiber connectors) is within the budget for most coherent and direct-detect data center receiver designs at 400G and beyond. System designers should verify receiver sensitivity margin against this figure plus the additional margins specified in §9.4.1.

6.6 Environmental and Reliability Standards

All FAU assemblies intended for data center deployment shall satisfy the following environmental and reliability requirements. Testing shall conform to the referenced IEC 60068 series procedures or equivalent JEDEC / Telcordia GR-1209 methods as applicable.

- Thermal operating range: FAU assemblies shall function within specification across the full commercial data center temperature range.
- Alignment drift over time (lateral): Long-term creep or adhesive relaxation shall not produce lateral misalignment exceeding ± 25 nm over 1,000 hours at maximum rated temperature.
- Alignment drift over temperature cycling (lateral): Repeated thermal excursions shall not produce cumulative misalignment exceeding ± 50 nm after 100 thermal cycles (0 °C to 70 °C).
- Shock and vibration drift: Following shock (50 g, 11 ms half-sine) and vibration (2–500 Hz) events per IEC 60068-2-27 and IEC 60068-2-6 respectively, lateral alignment drift shall not exceed ± 50 nm (shock) or ± 30 nm (vibration).

Parameter	Symbol	Min	Max	Notes
Operating Temperature	T _{op}	0 °C	70 °C	Commercial data center range
Storage Temperature	T _{st}	–40 °C	85 °C	Unpackaged assembly
Alignment Drift — Time (lateral)	δ_t	—	± 25 nm	Over 1000 h at T _{max}
Alignment Drift — Thermal Cycling	δ_{tc}	—	± 50 nm	100 cycles, 0 °C - 70 °C
Alignment Drift — Shock (lateral)	δ_s	—	± 50 nm	Per IEC 60068-2-27, 50 g, 11 ms
Alignment Drift — Vibration (lateral)	δ_v	—	± 30 nm	Per IEC 60068-2-6, 2–500 Hz
Humidity (non-condensing)	RH	5 %	85 %	IEC 60068-2-78 conditions

Table 25 — Environmental and Reliability Requirements

6.7 PIC Coupling Building Block Standards

PIC coupling building blocks are the on-chip structures that transfer optical power between the external fiber/FAU system and the photonic integrated circuit waveguide network. This section specifies minimum performance requirements for the two principal coupler architectures used in data center PICs: edge couplers and grating couplers.

6.7.1 Edge Coupler Standards

Edge couplers transfer optical power at the chip facet through evanescent or mode-matched coupling from a cleaved, polished, or lensed fiber end-face. They are the preferred coupling architecture for low-loss, broadband, and polarization-insensitive operation.

- Fiber type compatibility: Specify compatible fiber types (SMF, lensed SMF, MCF channel); include MFD range supported.
- Device footprint: Overall device footprint in the chip plane, including inverse taper region. Reported as length (μm) $\times$ width (μm).
- Mode field diameter at output: Output MFD at the chip facet shall be documented and matched to the target fiber MFD within $\pm 10\%$.
- Numerical aperture: Output NA at the chip facet; shall be within ± 0.01 of fiber NA for low-loss coupling.
- Polarization behavior: State whether the coupler is polarization-insensitive, TE-only, or TM-only. Polarization-insensitive designs shall meet the PDL limit in Table 8.6.1-1. Single-polarization designs shall specify TE or TM extinction ratio.
- Center wavelength(s): Nominal design center wavelength(s) in nm. Specify per operating band (O-band: 1310 nm, C-band: 1550 nm, or multi-band).
- Bandwidth: Report 1 dB and 3 dB bandwidths from center wavelength.
- Insertion loss: Peak coupling efficiency expressed as dB loss at center wavelength.
- Reflection loss: Back-reflection suppression into the on-chip waveguide. Angled facet geometry strongly recommended.

Parameter	Symbol	Min	Max	Notes
Compatible Fiber Types	—	—	—	SMF, lensed SMF, MCF
Device Footprint	$L \times W$	—	TBD μm^2	Taper length $\times$ waveguide width
Mode Field Diameter (output)	MFD	TBD μm	TBD μm	Matched to target fiber MFD
Numerical Aperture	NA	—	0.20	At chip facet
Center Wavelength(s)	λ_c	—	—	O-band: 1310 nm; C-band: 1550 nm
1 dB Bandwidth	BW_1dB	40 nm	—	Per supported band
3 dB Bandwidth	BW_3dB	80 nm	—	Per supported band
Insertion Loss	IL	—	1.0 dB	Intrinsic; at center wavelength
Reflection Loss	RL	40 dB	—	Angled facet recommended
Polarization Insensitivity (IL Δ)	PDL	—	0.5 dB	TE vs TM at center λ
TE-only IL (if polarization-selective)	IL_TE	—	0.8 dB	N/A if polarization-insensitive
TM-only IL (if polarization-selective)	IL_TM	—	0.8 dB	N/A if polarization-insensitive

Table 26 — Edge Coupler Performance Requirements

NOTE: PDL = Polarization-Dependent Loss. Polarization insensitivity limit of 0.5 dB applies to designs intended for polarization-diverse applications. Single-polarization (TE-only or TM-only) designs are exempt from this limit but must state polarization mode in the device specification.



6.8 Grating Coupler Standards

Grating couplers transfer optical power between an out-of-plane fiber and an in-plane PIC waveguide through periodic diffraction structures etched into the chip surface. They enable wafer-scale testing and flexible fiber placement but typically exhibit higher insertion loss and narrower bandwidth than edge couplers.

- Fiber type compatibility: Specify compatible fiber types and whether single-channel or MCF grating array is intended.
- Device footprint: Overall grating aperture and taper region dimensions in $\mu\text{m} \times \mu\text{m}$.
- Target fiber MFD: The fiber MFD that the grating is designed to accept, in μm . Grating period and apodization shall be optimized for this MFD.
- Fiber coupling angle (θ_f): Angle of the fiber axis from the surface normal, in degrees. Shall be documented with tolerance ($\pm 0.5^\circ$). For silicon photonics, 8° – 15° is the standard range to suppress second-order reflections.
- Center wavelength(s): Nominal design center wavelength(s) per operating band.
- Operating band: Specify applicable operating band(s): O, E, S, C, or L. Multi-band grating arrays shall specify per-band performance.
- Wavelength division scheme: State whether the coupler is wavelength-agnostic, or optimized for a specific CWDM or DWDM channel plan.
- Bandwidth: Report 1 dB and 3 dB bandwidths.
- Polarization behavior: State design intent — polarization-insensitive, TE-only, TM-only, or polarization-splitting (2D grating). Relevant limits apply per Table 15.
- Polarization splitting performance: For 2D polarization-splitting gratings, specify polarization extinction ratio (PER) between TE and TM output ports.
- Insertion loss: Peak coupling efficiency in dB at center wavelength and optimal fiber angle.
- Reflection loss: Back-reflection from the grating into the on-chip waveguide mode.

Parameter	Symbol	Min	Max	Notes
Compatible Fiber Types	—	—	—	SMF, MMF, MCF (per grating design)
Device Footprint	$L \times W$	—	TBD μm^2	Grating area including taper
Target Fiber MFD	MFD _f	—	TBD μm	Matched to fiber used
Fiber Coupling Angle	θ_f	8°	15°	From surface normal; SiPh standard
Center Wavelength(s)	λ_c	—	—	O-band: 1310 nm; C-band: 1550 nm
Operating Band	—	—	—	O, E, S, C, or L; specify per design
Wavelength Division Scheme	WDM	—	—	None / CWDM / DWDM; state applicability
1 dB Bandwidth	BW _{1dB}	30 nm	—	Per band
3 dB Bandwidth	BW _{3dB}	60 nm	—	Per band
Insertion Loss (peak)	IL	—	2.0 dB	At center wavelength, optimal angle
Reflection Loss	RL	20 dB	—	Back-reflection into waveguide
Polarization Insensitivity (IL Δ)	PDL	—	1.0 dB	2D grating targets < 0.5 dB
TE-only IL (if applicable)	IL _{TE}	—	2.0 dB	1D TE grating configuration
TM-only IL (if applicable)	IL _{TM}	—	2.0 dB	1D TM grating configuration
Polarization Splitting Extinction	PER	20 dB	—	For 2D polarization-splitting grating

Table 27 — Grating Coupler Performance Requirements

NOTE: Insertion loss values are significantly process-dependent. Apodized and partially-etched designs may achieve < 1.0 dB IL; standard uniform gratings typically exhibit 2–3 dB. Design teams shall document achieved IL with process corner data (typ, min, max) across the wafer.

7.0 Multicore Fiber Array Unit (FAU) to Photonic Integrated Circuit (PIC) Interface Examples

7.1 One-Dimensional Multicore Fiber Array (FAU) - Fiber Orientation for Edge Coupling

The figure below shows the 4 core Multicore fiber orientation within a representative one-dimensional 16-fiber array unit (FAU) with a 127 μm pitch; this approach can be applied to typical 250 μm fiber pitches.

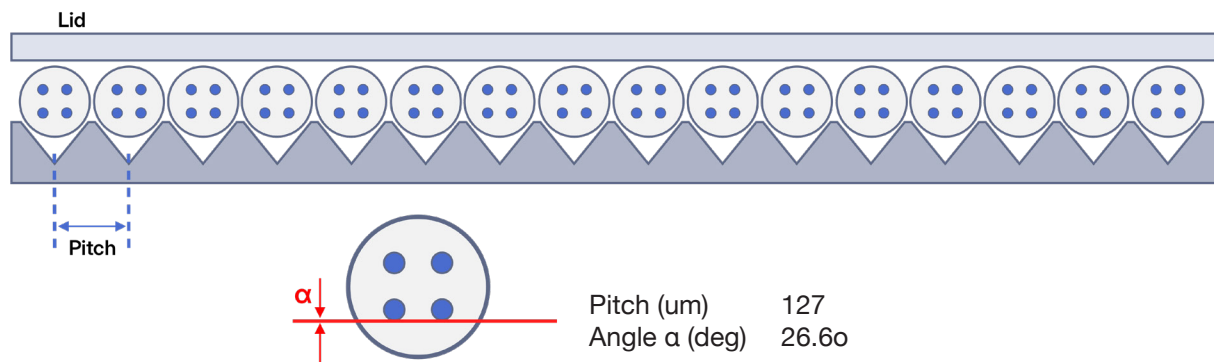


Figure 34 — Multicore Fiber Interface after Connector, Type 1

Parameter	Requirement
Pitch (μm)	127
Angle α (deg)	0 deg

Table 28 — Parameters of Multicore Fiber interface after connector, Type 1

An intermediate or transition part is needed to convert the 2-D geometry of the 4-core Multicore fiber into a 1-D geometry compatible with edge coupled waveguides. Several technologies exist to solve this problem, including fiber bundled FIFOs and 3D waveguides.

7.2 One-Dimensional Multicore Fiber Array (FAU) – Fiber Orientation for Vertical Coupling to Grating Coupler

The figure below shows the 4 core Multicore fiber orientation within a representative one-dimensional 16-fiber fiber array unit (FAU) with a 127 μm pitch; this approach can be applied to typical 250 μm fiber pitches. This fiber orientation is optimized for a grating coupler layout. 16-fiber fiber array unit (FAU) with a 127 μm pitch; this approach can be applied to typical 250 μm fiber pitches.

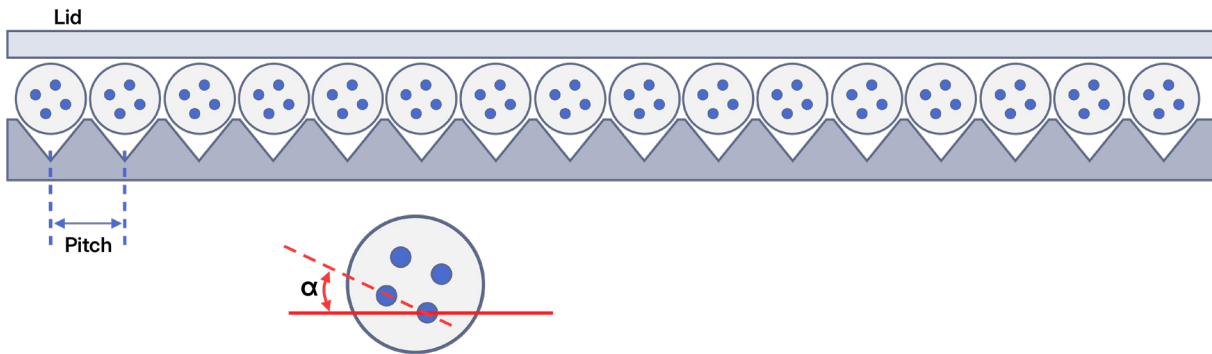


Figure 35 — Multicore Fiber interface after Connector, Type 2

Parameter	Requirement
Pitch (um)	127
Angle α (deg)	26.6o

Table 29 — Parameters of Multicore Fiber interface after connector, Type 2

A representative Photonic Integration Circuit (PIC) emitting point arrangement is shown below.

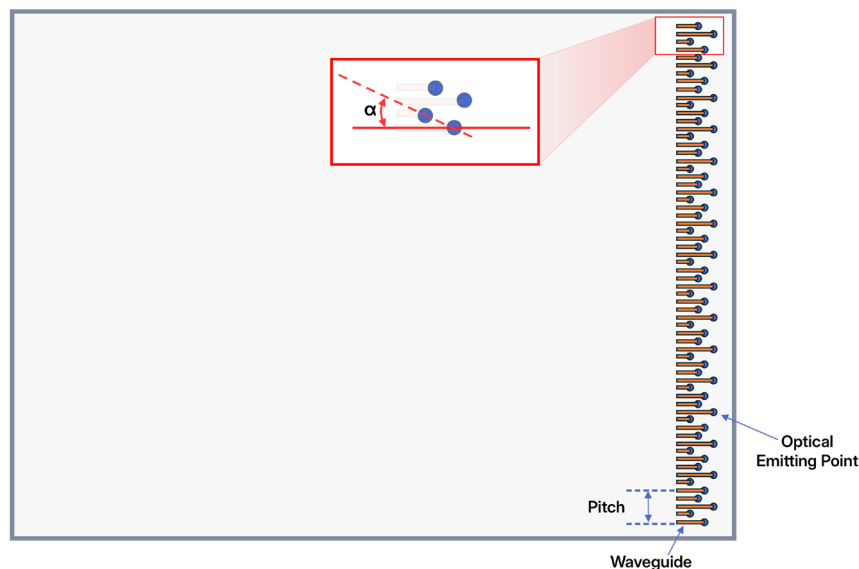


Figure 36 — PIC Surface Emitting Point Arrangement

8.0 Terms & Definitions

Terms

Definitions

Artificial Intelligence and Machine Learning	Systems requiring high-speed data movement and processing.
Co-Packaged Optics	Optical engines integrated near switch ASICs to increase bandwidth and reduce power.
Co-propagating	MCF transmission mode where all cores carry signals in the same direction.
Counter-propagating	MCF transmission mode where transmit and receive signals share different cores.
dB	Logarithmic unit used to measure optical power gain or loss.
Datacenter	Facility housing computing, storage, and networking infrastructure.
Dual-LC	Pair of LC connectors supporting duplex optical communication.
Edge Coupler	Optical interface coupling light between a PIC and optical fiber.
End-of-Life	Point at which a product is no longer manufactured or supported.
Fan In / Fan Out	Device that combines or separates optical channels between fiber arrangements.
FAU Interfaces	Mechanical and optical connection points for Fiber Array Unit attachment.
Fiber Array Unit	Precision assembly aligning multiple optical fibers to photonic devices.
First-In, First-Out	Data buffering method preserving transmission order.
Gigabit	One billion bits of data transmission capacity.
Grating Coupler	PIC structure that couples light vertically between fiber and chip.
High-Performance Computing Data Centers	Facilities supporting large-scale scientific, engineering, and AI workloads.
IEC 60304	International standard defining preferred numerical values and series.
Leaf/Spine	Network architecture providing scalable, low-latency data center connectivity.

Terms & Definitions (con't)

Terms	Definitions
Micrometer	One-millionth of a meter.
Miniature Multi-Fiber Connector	Optical Interface Multi-fiber optical connector interface supporting high-density optical links.
Multicore Fiber	Optical fiber containing multiple independent cores within a single cladding.
Multi-Fiber Push-On Connector	Supporting multiple fiber terminations.
Photonic Integrated Circuit	Combining multiple optical functions on one chip.
Polarization Maintaining	Fiber designed to preserve light polarization state.
Scale-Out Networks	Networks expanded by adding additional nodes or systems.
Scale-Up Networks	Networks expanded by increasing capacity within existing systems.
Shuffle Connect	Fiber management method redistributing optical connections between connector groups.
Single-Mode Fiber	Designed to support one optical transmission mode.
SN-MT / Senko Nano Mechanical Transfer	Very small form factor duplex fiber optic connector interface developed by SENKO.
Space Division Multiplexing	Technique increasing capacity by transmitting over multiple spatial paths.
Terabit	One trillion bits of data transmission capacity.
TIA-598	Standard defining color coding for optical fiber identification.
Transceivers	Devices that transmit and receive optical or electrical signals.
Very Small Form Factor	Compact connector design enabling increased fiber density and port count.

9.0 Acronyms

Acronym

AI/ML	Artificial Intelligence and Machine Learning
ASIC	Application-Specific Integrated Circuit
CPO	Co-Packaged Optics
dB	Decibel
DC	Datacenter
EoL	End-of-Life
FIFO	Fan in/Fan out
FAU	Fiber Attached Unit
G	Gigabit
HPC	High-Performance Computing
LC	Lucent Connector
MCF	Multicore Fiber
MMC	Miniature Multi-Fiber Connector
MPO	Multi-Fiber Push-On Connector
PIC	Photonic Integrated Circuit
PM	Polarization Maintaining
RX	Receive optical signal path or receiver function.
SMF	Single-Mode Fiber
SN-MT	Senko Nano Mechanical Transfer
SDM	Space Division Multiplexing
T	Terabit
TRx	Combined transmit and receive optical communication function.
TX	Transmit optical signal path or transmitter function.
μm	Micrometer
VSFF	Very Small Form Factor



Thank you



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