MULTI-CORE FIBERS FOR DATA CENTER APPLICATIONS

Tetsuya Hayashi, Takuji Nagashima, Tetsu Morishima, Yuki Saito, and Tetsuya Nakanishi*

Optical Communications Laboratory, Sumitomo Electric Industries, Ltd., Yokohama 244-8588 Japan
**t-hayashi@sei.co.jp*

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Abstract

We present and review the multi-core fiber (MCF) technologies suitable for data center applications. We also present the potential use cases of the MCFs, and discuss the benefits from MCFs in these applications.

1 Introduction

In long-haul optical fiber transmission systems, dense wavelength-division multiplexing (WDM) and higher-order modulation formats with coherent detection now allows the almost full utilization of efficient amplification wavelength band [1]. To address the further-growing capacity demands, space-division multiplexing (SDM) technologies have been intensively studied in recent years. Among various types of SDM fibers, the uncoupled multi-core fiber (MCF) is the most representative SDM fiber [2]. Multiple cores with moderate separations enable low inter-core crosstalk (XT) and simple fan-in/fan-out (FIFO) technologies compared to the other SDM fibers, which may realize high compatibility to the conventional transceivers (TRx) without the multiple-input-multiple-output (MIMO) digital signal processing (DSP) for compensating modal XT.

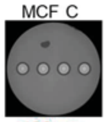
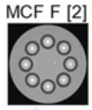
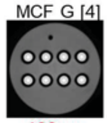
In short-reach interconnects, high-bandwidth (BW) and high-density optical interconnects have an important role for improving the performances of large-scale data centers (DCs) for reducing the bottlenecks in the switch I/O BW and the front panel BW [3]. Although optical fiber transmission capacity has not been fully utilized with no/coarse WDM and intensity-modulation direct-detection, it is not easy to fully leverage the single-core fiber capacity in DCs because of the strict limitations of TRx size, cost, and power dissipation. Under such practical short-reach TRx limitations, the MCF can be a good solution for improving the transmission link BW and density of short-reach interconnects, since multiple spatial channels can be densely integrated into a photonic integrated circuit (PIC) in a TRx.

In this paper, we present and review the MCF technologies applicable to the DC applications. We will also discuss some potential use cases of the MCFs in DCs.

2 Multi-Core Fibers

Although various types of MCFs have been proposed in the research, to leverage existing technologies and/or ecosystems, practical MCFs for DC applications must not change too many parameters like fiber dimensions and optical properties from existing standards. Our proposed MCFs (MCFs A–G) suitable for short-reach applications are shown in Tables 1,2. All the fibers are compatible with the standard 250-µm-diameter coating. In Table 1, the MCFs are categorized by required FIFO dimensionality (2D/3D), operating wavelength band (λ_{op}), and core count. Table 2 summarizes the properties of the MCFs. The MCFs with linear (1×N) core layouts (MCFs A–C) can be coupled to planar waveguides such as planar lightwave circuits (PLCs) or the edge couplers of PICs, at the sacrifice of the cladding space utilization. However, as discussed in Section 3.2, PLC-based 2D fan-in/fan-out (FIFO)

Table 1 MCFs for short-reach applications categorized by required FIFO dimensionality (2D/3D), operating wavelength band (λ_{op}), and core count.

FIFO	λ_{op}	2-core	4-core	8-core
2D	O band	MCF A [2]  125 µm	MCF B  125 µm	n/a
2D	O to L band		MCF C  180 µm	n/a
3D	O band		MCF D [3]  125 µm	MCF E [1,2]  125 µm
3D	O to L band			MCF F [2]  150 µm; MCF G [4]  180 µm

*The number under each MCF represents the cladding diameter. All the fibers are compatible with the standard 250-µm-diameter coating.

Table 2 Properties of the MCFs shown in Table 1.

ID	FI-FO	λ_{op}	OD [µm]	Core #/type	Λ [µm]	MFD† [µm]	XT‡ [dB/km] 1310	XT‡ [dB/km] 1550	Ref.
A	2D	O–L	125	2/SI	45	8.5	n/a	<−40	[4]
B	2D	O	125	4/SI	28	6	<−50	n/a	n/a
C	2D	O–L	180	4/TA	39	8.5	n/a	~ −50	n/a
D	3D	O–L	125	4/TA	40	8.5	n/a	~ −60	[5]
E	3D	O	125	8/TA	31	8.4	≤−62	n/a	[4,6]
F	3D	O–C	150	8/TA	32	8.5	≤−58	<−50	[4]
G	3D	O–L	180	8/TA	35x45	8.4	≤−66	≤−42	[7]

†Value at λ = 1310 nm. ‡Total crosstalk to a core at λ [nm] in the bottom row of the column heading. *All the fibers have the cable cutoff wavelength of less than 1260 nm, and are compatible with the standard 250-µm-diameter coating.

can be mass-producible with conventional technologies, and the link cost of the 1×N-core fibers could be competitive especially in the early stage of MCF deployments. In the 1×N-core fibers, the 1×2-core fiber (MCF A, [4]) can support O to L band within a standard 125-μm cladding, but the 1×4-core fibers (MCFs B/C) can support only O band in a 125-μm cladding (MCF B) or O to L band in a thicker 180-μm cladding (MCF C). 1×8-core fibers would be difficult to be realized in practical optical properties and cladding thickness. On the other hand, the MCFs with 2D core layouts (MCFs D–F) can achieve higher density. The 4-core fiber with square-lattice core layout (MCF D, [5]) can support O to L band. Circularly-arranged 8-core fibers (MCFs E/F) can support O band within a 125-μm cladding (MCF E, [4,6]) or O to L band in a 150-μm cladding (MCF F, [4]). A 2×4-core fiber with a 180-μm cladding can support O to L band, and can be directly coupled to Si Photonics chip with surface coupling devices like grating couplers (see Section 4.1). However, of course, these MCFs requires 3D waveguides as FIFOs (see Section 3.2).

3 Connectivity

3.1 MCF Connectors

MCF connections require rotational fiber alignments to realize a low insertion loss (IL). In single-fiber connectors, ferrule floating structure must be implemented to isolate the ferrule from external stresses to plug frame. However, the ferrule must be rotationally aligned with reference to the plug frame. Table 3 shows our design approaches for simultaneously realizing rotational alignment and ferrule floating in SC and MU/LC single-MCF connectors [8]. The conventional SC connector have a large clearance between a ferrule flange and a plug frame, and the rotational misalignment can reach to ±3 degrees at most. By optimizing the clearance, the ferrule floating and precise rotational alignment can be simultaneously realized in the SC connector. In contrast to the SC connector, the MU/LC connector dimensions are too small to realize both the sufficient ferrule floating and precise rotational alignment by the clearance optimization. Therefore, we employed an Oldham coupling mechanism [9] inside MU/LC connectors, as shown in Fig. 1a. The Oldham coupling structure enables the vertical and horizontal floating movement of ferrules with less than ±0.5-degree rotational misalignment. Thanks to these precise alignment mechanisms, the IL of less than 0.5 dB has already been achieved in the SC, MU, and LC single-fiber MCF connectors [8].

In multi-fiber connectors like MT/MPO connector, fiber rotational alignment can be assured by guide pins and guide holes on a multi-fiber ferrule. So, we do not need a special structure between the ferrule and plug frame. However, MCF pre-alignment structure—e.g., (MT-insertable) V-groove array in Fig. 1b— is necessary to avoid rotational alignment difficulty due to fiber-ferrule friction in a small clearance high-precision ferrule [10]. We demonstrated 256-core (8-core × 32-fiber) MPO connectors with the IL of less than 1 dB [10] and the physical contact connection of all 256 cores [11].

Table 3 Approaches for realizing both rotational alignment and ferrule floating in single-MCF connectors [8].

	Conventional	Our approach
SC	±3° Plug frame Flange	±0.5° Clearance Clearance optimization
MU/LC	±10° Plug frame Flange	±0.5° Oldham coupling (see Fig. 1a)

3.2 Fan-In/Fan-Out Devices

Although end-to-end MCF transmission link can be realized without fan-in/fan-out (FIFO) devices [7], the interoperability to conventional SMF systems would be still important for the operation of DC networks, and the FIFO would be necessary. Since DC applications demands very high-volume interconnects, the FIFO device manufacturing must be scalable. In that sense, one of the most promising FIFO technologies is the planar lightwave circuit (PLC) technology (Fig. 2a). The conventional PLC technology [12] is compatible, of course, only to linear 1×N core layouts, since it is *planar* (2D). However, the PLC can be manufactured in low cost and high volume—both are different order of magnitude compared with other FIFO technologies at present—, which has been already proven in various telecom and DC applications. The MCFs with 1×N core layouts shown in Tables 1,2 are compatible with the PLC-based 2D FIFO. 3D FIFO can also

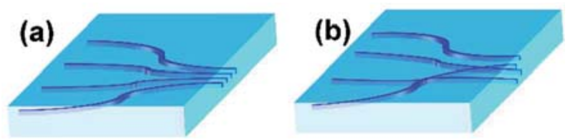


Fig. 2 Schematics of (a) 2D FIFO based on the planar lightwave circuit technology, and (b) 3D FIFO based on femtosecond laser inscription technology.

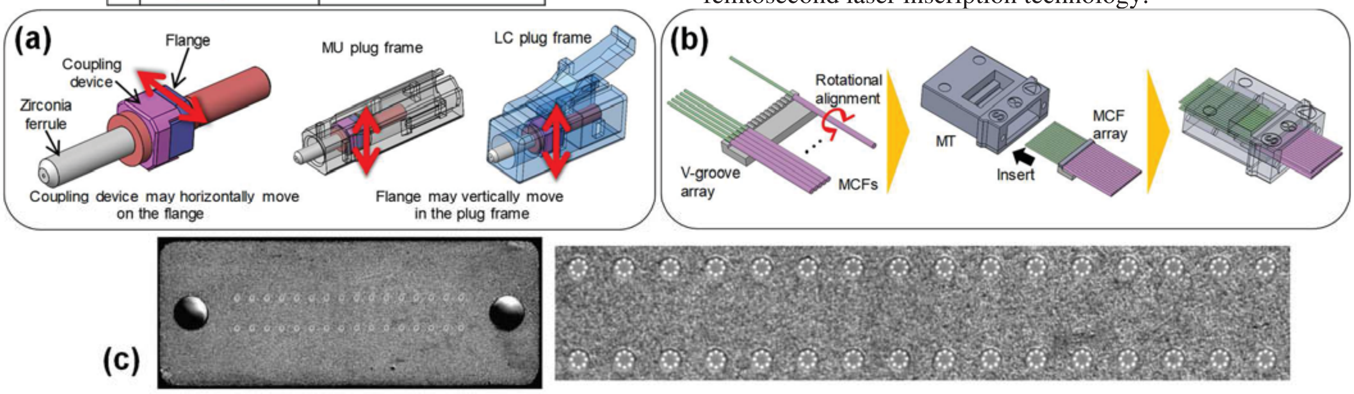


Fig. 1 (a) Oldham coupling mechanism in MU/LC connector, (b) schematics of MCF MT connector fabrication, and (c) the end face and its close-up of the fabricated 256-core (8-core × 32-fiber) MT ferrule [8,10].

be realized by stacking multiple PLCs [13], but the high-precision control of PLC thicknesses would be a challenge in mass production. Another promising option for the FIFO is the femtosecond laser inscribed 3D waveguide (Fig. 2b) [14]. Multi-beam processing technology [15] is expected to multiply the laser inscription productivity.

3.3 Passive rotational alignment by non-circular MCF

An MCF rotation angle can be actively aligned by monitoring the angle itself, but it is attractive if the MCF angle can be passively aligned. We developed an MCF with double-D-shape cladding [16], and demonstrated the accurate passive rotational alignment of the eight MCFs on a 90° V-groove array [17], as shown in Fig. 3. The standard deviation of the rotational misalignment was 0.36 degrees, and the IL of the outer cores of the 8 MCFs were achieved to be less than 0.50 dB with the average of 0.21 dB. The productivity and dimensional repeatability of the non-circular MCF are still challenges but the results showed the potential of the passive alignment of MCFs.

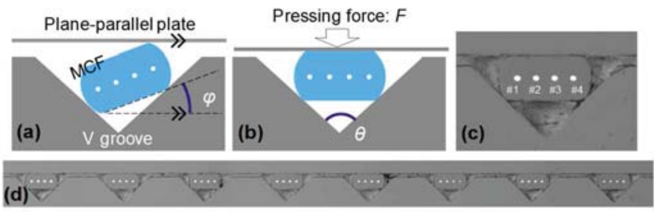


Fig. 3 Double-D-cladding MCFs on V grooves. (a,b) schematics of the passive alignment, (c) close-up of a MCF facet, and (d) the end face of the 8-fiber array, passively aligned on the V grooves [17].

3.4 MCF Splicing

MCF splicing requires the rotational alignment of fibers, but commercial specialty fiber splicers are already applicable to the MCF splicing [18,19]. The challenges for the use in DCs are splicer size and cost, and rotational alignment time and accuracy. Most of the currently available specialty fiber splicers equip various functions (not necessary for MCF splicing) to deal with various specialty fibers, which increases the size and cost of the splicers. The automatic alignment algorithms that can cope with MCFs are universal algorithms that do not require the specific assumptions on fiber structures, like a PANDA fiber, but take a longer time and are less accurate. However, simple and optimized MCF splicers could be developed, once MCF dimensions are determined by de fact/de jure standards or multi-source agreements (MSAs).

4 Potential Use Cases

4.1 Low-Cost/High-Density Parallel Single-Mode Core Link

Parallel single-mode fiber transmission links in DCs like PSM4 [20] are good candidates of MCF applications. PSM4 link can be realized by 1 strand of 8-core fiber or 2 strands of 4-core fibers, which means that 8-SMF ribbon cable and 8-SMF MPO connectors can be replaced by 1-/2-MCF thinner cable and simplex/duplex single-MCF connectors. These simplifications of the cable and connectors could reduce the link cost. We, in collaboration with Luxtera, demonstrated end-to-end MCF transmission link with LC connectors by MCF-native Si Photonic TRx based on PSM4, where co-designed grating coupler array and MCF (MCF G) (Fig. 4) realized direct MCF coupling to Silicon Photonics chips [7]. We confirmed there are no significant degradations due to the use of the MCF.

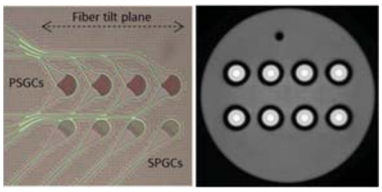


Fig. 4 Codesigned grating coupler (GC) array (left) and MCF (right) [7]. (PSGCs: polarization-splitting GCs for reception, SPGCs: single-polarization GCs for transmission)

4.2 Ultra-High-Density Trunk/Outside Plane Cable

Another strong candidate of MCF applications for DCs is the ultra-high-core-count cable [21]. MCFs can reduce the diameter and weight of the cable without changing the cable core count, as well as multiplying the core count in a cable without changing the cable diameter. Fig. 5 shows an example of the relationships between the core count, diameter, and weight of ultra-high-density rollable-ribbon cables with SMFs or MCFs (8-core case). When we look at 3456-fiber cable, by using the 8-core fibers, the cable diameter and weight can be reduced by ~60% and ~90%, respectively, without reducing the core count in the cable. Such large reductions in the diameter and weight will make the cable installation much easier hence reduces the installation time and cost. To investigate the applicability of MCFs to ultra-high-density cables, we fabricated and evaluated an 12-fiber indoor round cable with the 125-μm-cladding 8CF (MCF F) [6,22], and 100-fiber rollable ribbon outside plant cable with 125/150-μm-cladding 2/8-core fibers (MCFs A,E,F) [4]. We confirmed good optical performance of the MCFs even after the cabling.

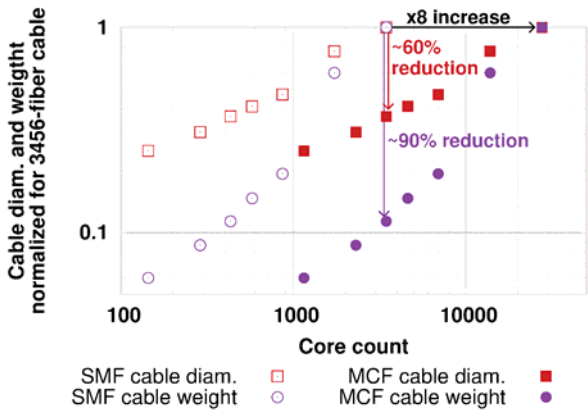


Fig. 5 Comparison of core count, diameter, and weight between SMF and (8-core) MCF rollable-ribbon cables.

5 Conclusion

The MCF technologies have been steadily growing including their peripheral technologies, and now we can see economically viable potential use cases. Continuous development of MCF technologies will enable and accelerate practical deployments of MCFs in DCs in near future.

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7 References

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