Core Number Management of Weakly Coupled Multicore Fibre Supporting Uniform Transmission Among Cores

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Abstract *A novel connection structure for multicore fibre (MCF) is proposed to enhance the uniformity of optical properties among cores in MCF links by utilising the natures of polarity and rotation while maintaining core number identification. ©2023 The Author(s)*

Introduction

Weakly coupled multicore fibres (MCFs) with standard cladding diameters are expected to be used in the early stages of space-division multiplexing. Particularly, various technologies, such as fibres, connectivities, and transmission technologies, have been studied in four-core MCF (4CF). Standardisation activities have also advanced [1].

Recently, operational challenges, such as the uniformity of cores in transmission and core number identification, have been identified [2]. Some reports have shown the nonuniformity of optical properties among cores, such as link loss, splice loss, and inter-core crosstalk (IC-XT) [3, 4]. An approach known as the inline cyclic core permutation has been reported to improve the uniformity of inter-core skew and splice loss [5]. However, limiting the number of segments was necessary to manage core number identification. We propose a novel method for core number management to reduce the management burden of MCF polarity while maintaining the core number identification [6]. In this study, we further develop this concept and propose a suitable connection structure that supports the uniformity of optical properties among cores.

Moreover, separating the cause of nonuniformity in individual factors was difficult in previous studies [3, 4] because 4CFs made by multiple vendors were used. We investigated the core number dependency of optical properties using 288-4CFs cable reported previously [7]. Although the population showed high uniformity of attenuation and IC-XT among cores, some individual MCFs showed a 10% nonuniformity in attenuations.

Nature of polarity in MCF

A marker is placed in the MCF where the core symmetry is broken, enabling each individual core to be distinguished by its distance from the marker. This generates polarity in the MCF. Fig. 1 (a) shows the polarity of 4CF and the core numbering used in this study. The core numbering patterns of the 4CF differ between two ends; they are mirror-symmetrical. Ends A and B exist as sets at either end of the MCF. Fig. 1 (b) shows the polarity of the fan-in fan-out (FIFO) devices. An MCF pigtail is attached to the device, and port numbers are assigned to each single core fibre (SCF) based on the core numbers of the MCF pigtail. A FIFO device also has two polarities, depending on the polarity of the MCF pigtail.

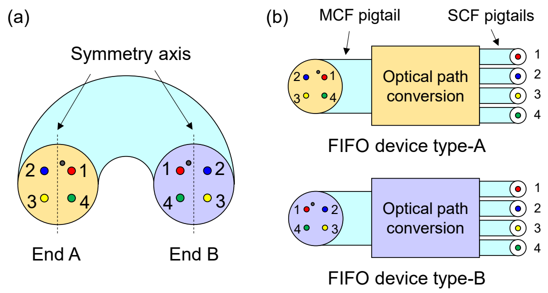


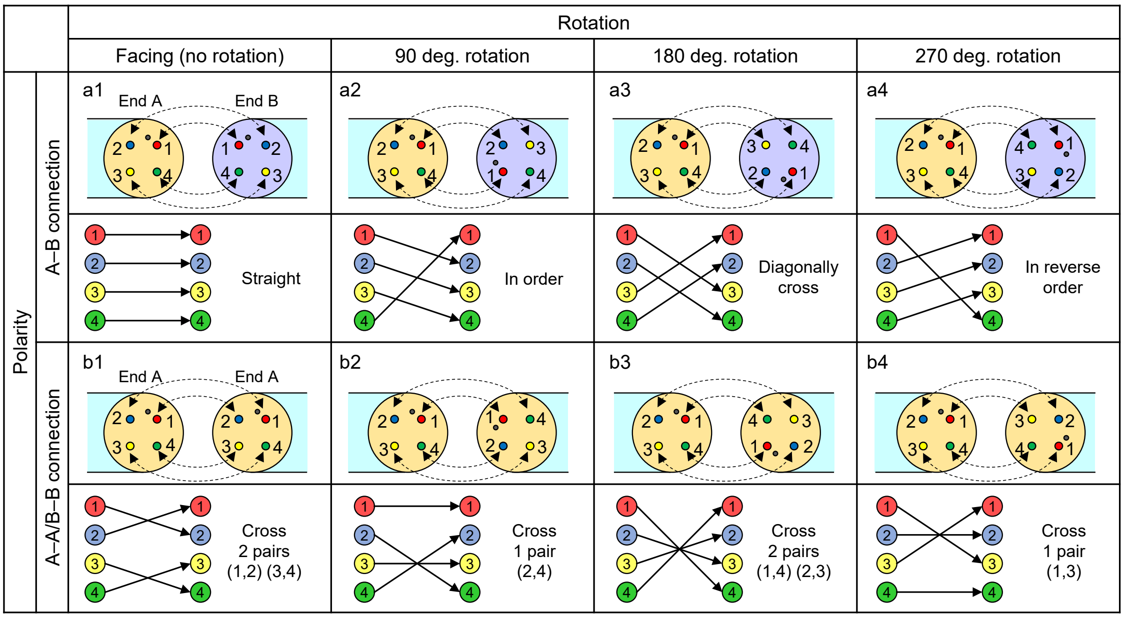
Fig. 1: Definition of polarity and core numbering in (a) MCF and (b) FIFO device.

Rotation and polarity must be considered when connecting two 4CFs, such that their core numbers are managed. Tab. 1 lists the connection patterns of the core numbers when both the rotation and polarity are considered. Two polarity directions and four axial rotation directions result in eight possible connection patterns from ‘a1’ to ‘b4’. Connecting ends A and B are referred to as the A–B connection, which corresponds to patterns ‘a1’ to ‘a4’ in Tab. 1. In contrast, connecting ends A (or ends B) are referred to as the A–A (or B–B) connection, which corresponds to patterns ‘b1’ to ‘b4’ in Tab. 1.

MCF connection structure facilitating polarity management and core uniformity

Structures 1, 2, and 3 in Fig. 2 show the three MCF link structures in terms of polarity and connected core number. Three MCFs were connected at two connection points: MCF_west and MCF_east were assumed to be the MCF pigtails attached to the FIFO devices, and MCF_middle was assumed to be the MCF in the cable. The polarity state of each MCF is also

Tab. 1: Correspondence list of connected core number by rotation and polarity for 4CF connection.



indicated. In structures 1 and 2, ends A and B are arranged such that all connection points become A–B connections. In contrast, MCF_middle was flipped in structure 3, and all connection points became A–A/B–B connections. Fig. 2 shows the block diagrams of the core numbers to be connected.

In structure 1, the ‘a1’ pattern in Tab. 1 is assumed to be conducted at two connection points. Core #N in MCF_west is connected to core #N in MCF_middle and is connected to core #N in MCF_east. In contrast, the ‘a3’ pattern is assumed to be conducted in structure 2, while ‘b1’ pattern is conducted in structure 3. Evidently, core #N in MCF_west is connected to a different core #M in MCF_middle but is connected to core #N again in MCF_east in both structures 2 and 3. This is because the connected core number returns to the original value when the two junctions have the same connection pattern for patterns ‘a3’, ‘b1’, ‘b2’, ‘b3’, and ‘b4’. In summary, the end-to-end links had the same connection pattern in these three structures, although the number of connected cores differed along the route. In structures 2 and 3, the number of connected cores changes each time an MCF is connected. In such cases, the signal does not need to remain at a particular core number. Therefore, structures 2 and 3 are suitable for improving the uniformity of optical properties among cores.

This logic can be applied to a generalised case in which a number of MCFs are connected. If the polarity relationship between the MCFs at both ends of the entire link is fixed, both A–B and A–A/B–B connections occur an even number of times, regardless of the polarity state of the MCFs in the middle. Consequently, the end-to-end link

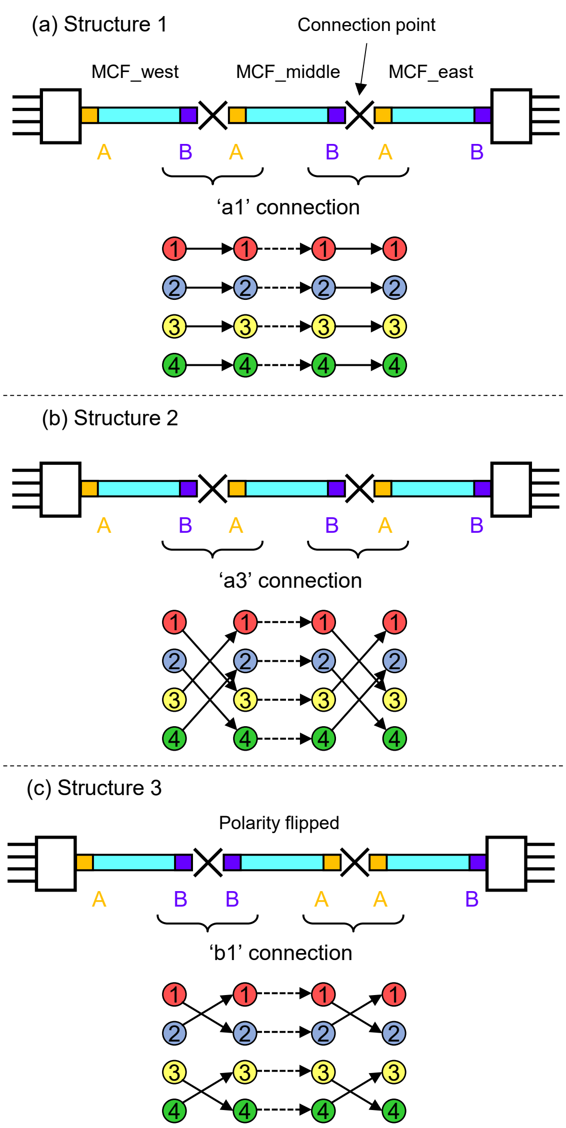


Fig. 2: MCF link structures and block diagrams of connected core number for each structure.

exhibits the same connection pattern if a specific connection pattern is followed. Furthermore, the more the polarity states of the MCFs along the route are mixed (i.e., the more A–B and A–A connections occur alternately, the more frequently the switching of the connected core number fluctuates). Therefore, selecting an appropriate connection pattern and allowing the polarity to be aggressively mixed are recommended to improve the uniformity of the cores during transmission. The verification of the workability of this proposal through field testing will be required in the future.

Investigation of core uniformity in MCF cable

We investigated the core number dependency of the optical properties using 288-4CF cables reported in [7]. This cable accommodated 4CFs made from two different MCF preform batches, and eight-core rods from three different batches were used in these preforms.

Fig. 3 shows the core number dependency of the attenuation and total IC-XT at 1550 nm. The total IC-XT is the sum of XT components received by a particular core from the other three cores. The sample size of the attenuation for each core was 288 and that of the total IC-XT was 24. The error bars indicate the maximum and minimum values in each core. Both attenuations and total IC-XT exhibited no significant differences among cores, indicating a high degree of uniformity across the population.

Subsequently, we examined the inter-core variations of the attenuation and total IC-XT to investigate individual differences, where the inter-core variation indicates the difference between the maximum and minimum values in four cores of a single MCF. Fig. 4 shows the histogram of the inter-core variation in attenuations. The average value was 0.011 dB/km with a maximum value of 0.027 dB/km. This result suggests that there was a 10% inter-core variation in the attenuations of some individuals. Fig. 5 shows the histogram of inter-core variation in total IC-XT. The average value was 2.7 dB/km with a maximum value of 3.8 dB/km. This difference is not considered significant because XT measurements result in a few dBs of variation.

These results indicate that individual MCFs may exhibit some degree of nonuniformity in attenuation among cores, even if they show high uniformity across the population. This means that the nonuniformity of link loss could be significant due to individual differences in MCFs when the number of segments in the MCF link is small. In such cases, our proposal could contribute to the improvement of the uniformity of link losses

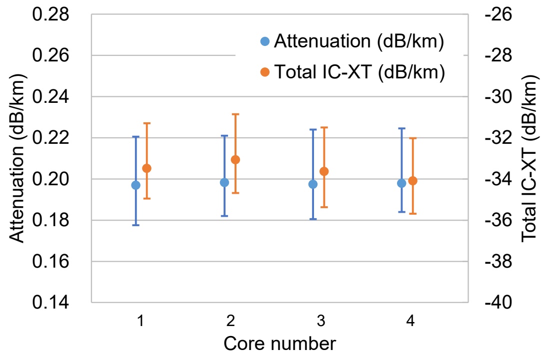


Fig. 3: Core-number dependency of attenuation and total IC-XT in the 4CF cable, both measured at 1550 nm.

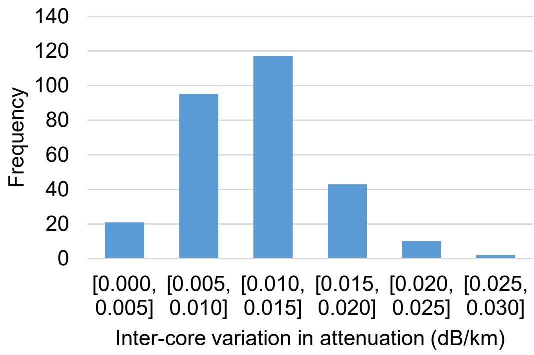


Fig. 4: Histogram of inter-core variation in attenuation.

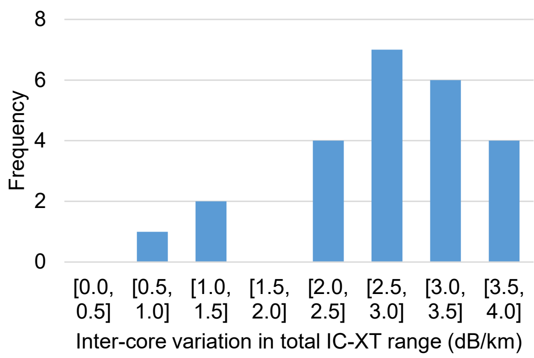


Fig. 5: Histogram of inter-core variation in total IC-XT.

among cores. In the future, the core number dependency of other optical parameters, such as inter-core skew and connection loss, must be investigated. As studies progress, a better understanding of the core number dependency of various optical properties is expected to be gained.

Conclusions

We proposed a core number management approach for MCFs that can reduce the nonuniformity of optical properties among cores while maintaining core number identification. The nonuniformity is suggested to be more pronounced for MCF links with fewer segments, which are more affected by individual differences in MCFs.

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