Connector Type Fan-out Device for Multi-core Fiber

Osamu SHIMAKAWA*, Hajime ARAO, Manabu SHIOZAKI, Tomomi SANO and Akira INOUE

The space division multiplexing (SDM) system using multi-core fiber (MCF) with plurality cores in one fiber is one of the promising candidates to overcome the capacity limitation of conventional fiber. To achieve practical use of MCF, a fan-out device that allows each MCF core to be connected into individual single-core fiber (SCF) is indispensable. The authors have developed a pluggable fiber bundle type fan-out for MCF using an SC connector, which has low coupling loss of less than 0.5dB, low crosstalk of less than -50dB and high return loss of more than 50dB.

Keywords: multi-core fiber, fan-out, connector, space division multiplexing

1. Introduction

The amount of the data traffic in optical communication networks has been exponentially increasing since the practical use of the wavelength division multiplexing (WDM) was achieved in the 1990s. Currently, it is growing at an annual rate of more than 40%[1]. As it is growing, optical input power per fiber is also increasing, and the fiber capacity is reaching its limitation. Several factors contribute to this limitation. One of them is the fiber fuse phenomenon. When high energy is concentrated in a fiber core whose diameter is about 10 µm, it is thermally destroyed. Hence, the transmission rate of 100 Tbit/s is considered to be the limit in transmission systems using conventional fibers. One of the promising candidates to overcome this limit is the space division multiplexing (SDM)[*1] system using multi-core fiber (MCF). **Figure 1** shows an example of MCFs we have developed[2]. This MCF consists of a center core and six hexagonally arranged outer cores to achieve a high-density arrangement. At the same time, transmission tests of up to Pbit/s scale have been recently conducted[3]. Peripheral technologies, such as connection between MCFs or between MCF and a single-core fiber (SCF), are indispensable[4] in achieving practical use of SDM systems with MCF. **Figure 2** shows a schematic of a transmission system using MCF. A fan-in and a fan-out are devices that allow each MCF core to be connected into individual SCF. They are set up in back of the transceiver and in front of the receiver, respectively. In the case of amplifying each MCF core individually, fan-in/out devices are also needed in a repeater. We have developed a pluggable fan-in/out for MCF utilizing an SC connector. In this paper, we present the development challenges as well as the structure and the optical characteristics of these devices. Although their point of use distinguishes a fan-in and a fan-out, both of them have the same structure. Hence, we unify the name of them to fan-out.

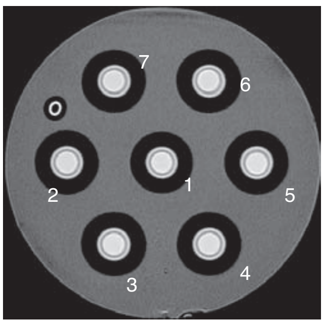

Fig. 1. Cross sectional view of MCF

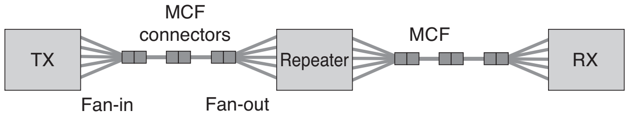

Fig. 2. Schematic of MCF transmission system

2. Challenges of Fan-out

2-1 New challenges

For SCF connectors used in conventional systems, a connection loss of less than 0.5 dB and a return loss of more than 40 dB are required. Even if an external force acts on them, these characteristics should be kept. The techniques and the structure for these purposes are shown in **Table 1** and **Fig. 3**, respectively.

However, when two MCFs are connected, new challenges (1) and (2) (shown below) have come up[5]. Moreover, when the MCF and a fan-out are connected, (3) is also important.

Table 1. Conventional connector techniques of SCF

Item	Technique
Low loss connection	Precise X/Y-axis alignments with high accuracy zirconia ferrules.
External force resistance structure	Floating ferrule structure to provide mechanical isolation from outside.
High return loss	Physical-contact (PC) of core area by deformation.

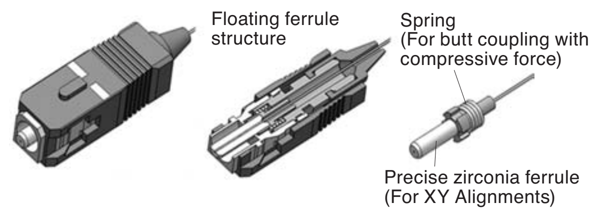

Fig. 3. SC connector structure

(1) Physical-contact (PC) of outer cores.
(2) Rotational fiber alignment.
(3) Geometric core position matching between a fan-out and MCF.

2-2 PC of outer core

The cross sectional schematic views of PC connectors are shown in **Fig. 4**. PC is achieved by deformation of spherically polished fiber end faces when a compressive force is applied to them. In the case of SCF, only the center core should make contact. On the other hand, in the case of MCF, the outer core also should make contact. To study the PC of MCF, the shape dispersion of the end face should be considered. In addition, there would be other problems such as an apex offset from the fiber center and a fiber withdrawal from the ferrule end face as shown in **Fig. 4**.

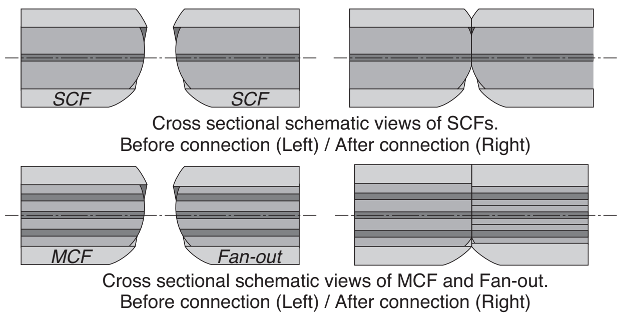

Fig. 4. Schematics of PC

2-3 Low loss connection

It is necessary to match the core arrangement of the fan-out with MCF and suppress the rotational misalignment in order to achieve low loss connection. **Figure 5** is the calculated results showing the relation between misalignment values and coupling loss, where the inter-core pitch is 45 μm and the mode field diameter (MFD)[*2] at 1.55 μm is 10 μm. If there is 1.5 μm X misalignment, the rotational misalignment should be smaller than 1 degree in order to keep the coupling loss at less than 0.5 dB.

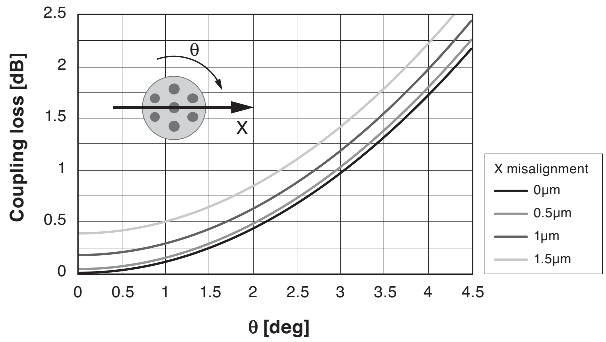

Fig. 5. Relation between misalignment and coupling loss (Calculated value)

3. Structure of Fan-out

3-1 Structure of fiber bundle

The structure of the developed fan-out is shown in **Fig. 6**. Seven thin fibers with cladding diameters of 45 μm are inserted and packed together in a ceramic ferrule to correspond with the MCF cores layout, and fixed by an adhesive. The cladding diameter of 45 μm is achieved by chemical etching. The other end of each fiber, with a cladding diameter of 125 μm, is inserted in a standard SC ferrule and put into an SC connector housing.

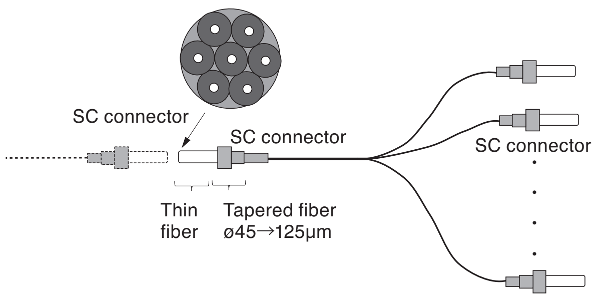

Fig. 6. Structure of fan-out

The appearance of an etched fiber is shown in **Photo 1**. When seven fibers are inserted into the hole of a ferrule, the clearance between the fibers and the inside wall of the

Photo 1. Etched fiber

ferrule would cause core eccentricities. Therefore, the fiber diameter should be controlled in order to make the clearance smaller than 1 µm. Stiffness of the thin-cladding fibers produced by drawing is not enough to be inserted in a hole smaller than 1 µm in clearance. On the other hand, an etched fiber has an advantage in that it is easily inserted into the hole of a ferrule, because it is tapered only at the end and is stiff. Moreover, the other side of the fiber can utilize standard connectors or standard fusion splicing techniques, because it has 125 µm cladding diameter.

The end face of a fiber bundle is shown in **Photo 2**. As can be seen, seven fibers with a cladding diameter of 45 µm are bundled closely in the ferrule hole with an inner diameter of 135 µm. It has the same core arrangement as that of MCF. The whole appearance of the fiber bundled fan-out is shown in **Photo 3**. The fiber bundle is housed inside the SC connector on the bottom-right corner, and it is pluggable with an MCF connector.

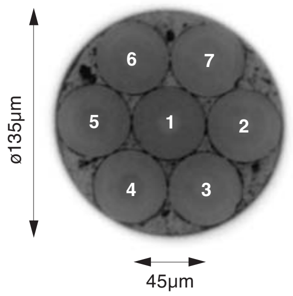

Photo 2. End face of fiber bundle

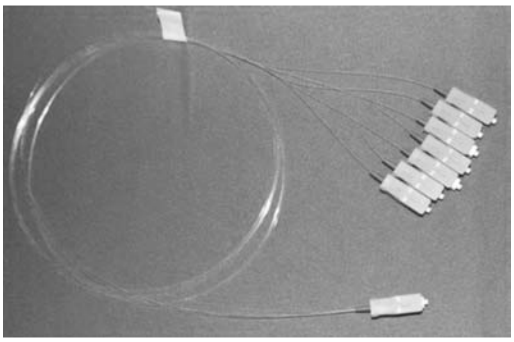

Photo 3. An entire fan-out

3-2 Core eccentricity of fan-out

The core eccentricities of the fabricated fan-outs are shown in **Fig. 7**. The dashed lines are results measured with reference to the center core position. Two connectors are usually aligned with each other by inserting their ferrules into a split sleeve. Hence, the results measured with reference to the center of ferrules are more important than those with reference to the center core. The solid lines in-

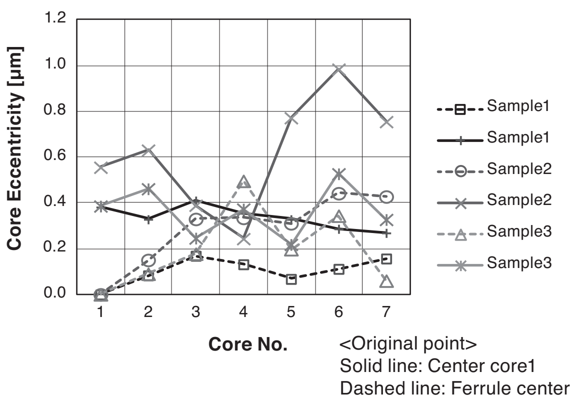

Fig. 7. Core eccentricities of bundle fibers

dicate the results reference to the center core. All results are smaller than 1 µm, confirming that the core eccentricities are small enough to achieve low loss connection.

3-3 SC connector housing

As mentioned in chapter 2-3, the rotational misalignment in an MCF connection should be controlled at smaller than ± 1 degree. In this MCF connector, the clearance between the notch and the key is reduced, but still in the range of normal operation of the ferrule floating. As a result, misalignment of smaller than ± 0.5 degrees is achieved (**Fig. 8**).

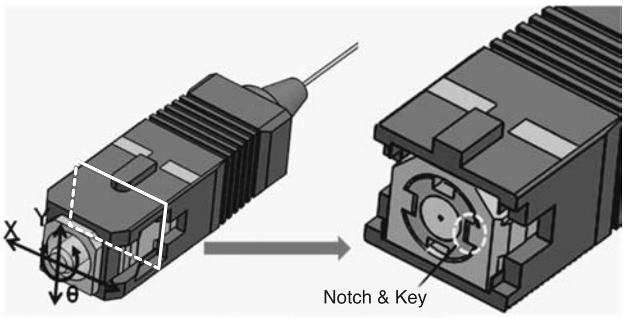

Fig. 8. Rotational suppression structure of SC connector

3-4 Connector end face shape

As mentioned in chapter 2-2, the end face shape and the compressive force condition of an SC connector should be reconsidered to achieve PC with all cores between the MCF and fan-out. The end face shape is decided by three parameters: the curvature radius of a fiber end face, the apex offset, and the fiber withdrawal (or the fiber protrusion). In addition to these, the compressive force is also a variable parameter for calculation. The constant parameters are the fiber cladding diameter, the core positions, and the physical properties of the materials. The PC condition can be calculated by these variables and constant parameters. We estimated the fiber end face shape to achieve PC by using the finite element method, when considering manufacturability. As a result, we clarified that PC can be achieved only by changing the range of the apex offset from the standard of our SCF connectors(6).

4. Optical Connection Characteristics between MCF and Fan-out

4-1 Connection loss

We evaluated the connection loss between MCF and the fan-out at room temperature. **Table 2** and **Fig. 9** show the fiber characteristics and the setup for measurement, respectively.

Table 2. Design of MCF and fiber bundle

Item	MCF	Fiber bundle
MFD (@1.55μm) [μm]	10	10
Inter-core pitch [μm]	45	45
Refractive index profile of core	Trench-assist [2]	Same as MCF
Cladding diameter [μm]	150	45

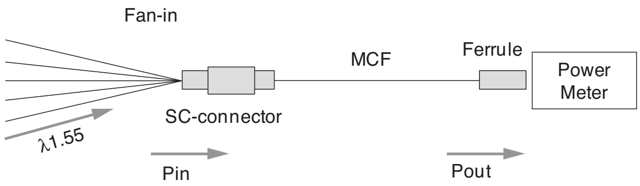

Fig. 9. Setup for connection loss measurement

The connection loss repeatability at 1.55 μm wavelength between the MCF and the fan-out is shown in **Fig. 10**. One pair of samples was mated 50 times. The average loss of the center core and the outer cores was 0.12 dB and 0.18 dB, respectively. The maximum loss was 0.18 dB and 0.44 dB, respectively.

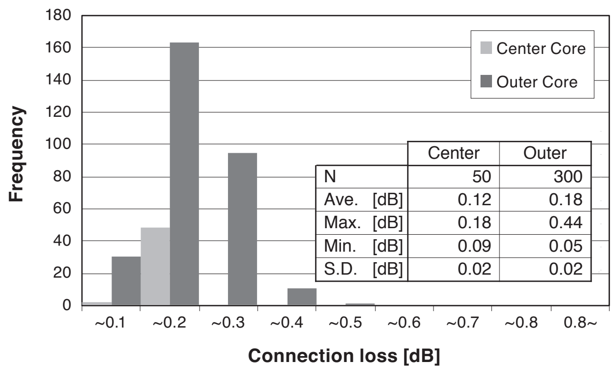

Fig. 10. Connection loss between MCF and fan-out

The loss changes of the fan-out connected with the MCF under a temperature cycling test of over -40 to 85 deg C is shown in **Fig. 11**. The loss changes of all 7 cores were stable at less than ±0.1 dB.

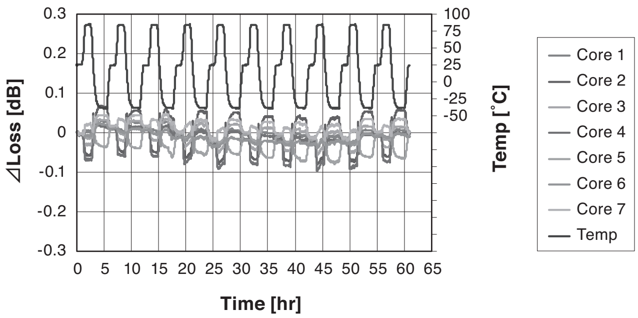

Fig. 11. Temperature dependent loss

4-2 Inter-core crosstalk

We evaluated the crosstalk of the fan-out connected with the MCF under a temperature cycling test of over -40 to 85 deg C. The setup for measurement is shown in the upper part in **Fig. 12**. The fan-in and the fan-out were connected on the each end of the MCF. A light of 1.55 μm wavelength entered into one port of the fan-in. We defined the crosstalk value as a proportion of one port power to the total port power in the fan-out as shown in the bottom part in **Fig. 12**. The results of the temperature dependent crosstalk, in the case of entering light from the center core of the fan-out, are shown in **Fig. 13**.

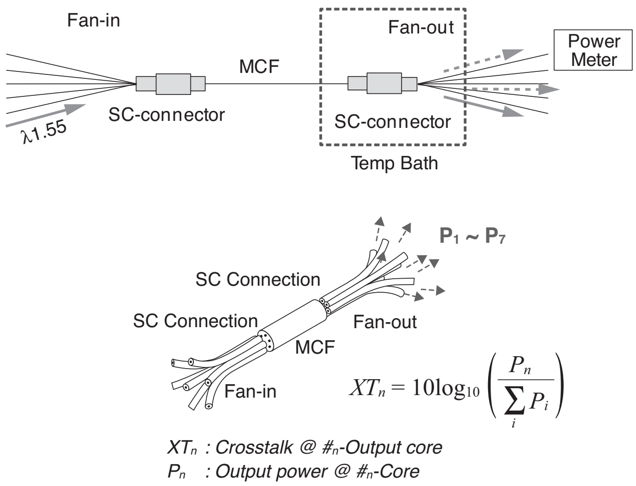

Fig. 12. Setup for crosstalk measurement (upper) and definition of crosstalk (lower)

All crosstalk of the fan-out is less than -50 dB, and confirmed to be low enough to be used. Also, crosstalk-changes are less than 2 dB. Core ID numbers are as shown in **Photo 2**.

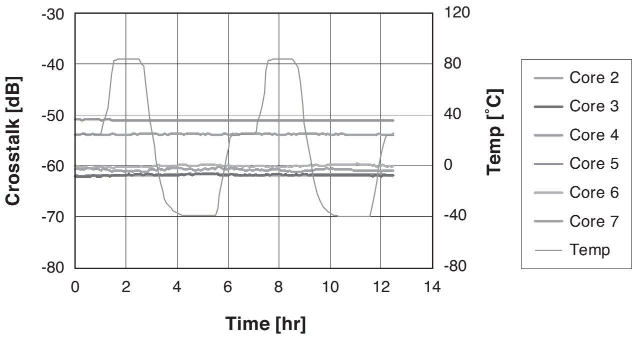

Fig. 13. Inter-core crosstalk (Center-core 1 input)

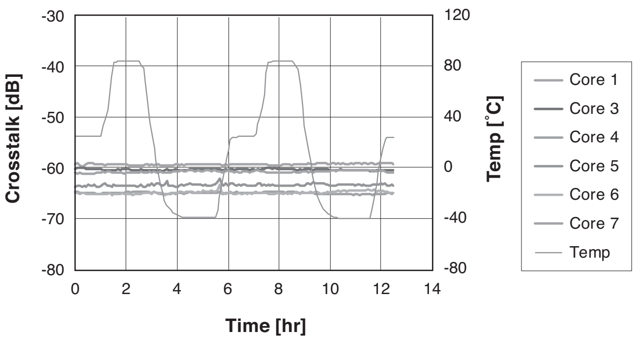

Fig. 14. Inter-core crosstalk (Outer-core 2 input)

The crosstalk, in the case of entering the light from outer core 2, is shown in **Fig. 14**. Since the center core 1 and outer cores 3 and 7 are adjacent to outer core 2, the crosstalk is higher than that of the other cores. Still all crosstalk is less than -58 dB, and confirmed to be low enough to be used. Also, crosstalk-changes are less than 3 dB, and low enough to be used.

4-3 Return loss

We measured the return loss of the fan-out connecting with an MCF at 1.55 μm wavelength. The results are shown in **Fig. 15**. The return loss of all cores is more than 40 dB, which is standard for conventional SCF connectors at over -40 to 85 deg C. This result means that PCs of all cores were kept at the wide temperature range.

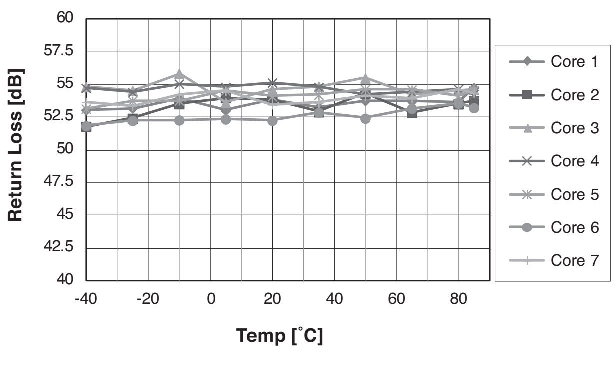

Fig. 15. Temperature dependent return loss

5. Conclusion

We fabricated a seven-core fiber bundle type fan-out with less than ± 1 μm core eccentricity. The pluggable fan-out connector for MCF was achieved by putting it into an SC connector housing. The connection loss of the fan-out to the MCF was less than 0.5 dB, which is as low as the standard value for conventional SCF connectors. The loss change of less than 0.1 dB, a crosstalk of less than -50 dB, and a return loss of more than 50 dB at over -40 to 85 deg C were also achieved. These results indicate that the fan-out has excellent temperature performance. In the future, MCF peripheral technologies such as a fan-in/out will become more important to achieve more than 100 Tb/s transmission capacity on a commercial level. We hope to continue to improve our fan-in/out and that this will contribute to the practical use of SDM systems.

6. Acknowledgements

This research was supported by the National Institute of Information and Communications Technology (NICT), Japan under the "Research on Innovative Optical Communication Infrastructure Technologies" initiative.

Technical Terms

*1 Space division multiplexing (SDM) : SDM is a method that uses multiple transmission lines simultaneously. In this paper, simultaneous signal transmission using plurality cores in one fiber is called SDM utilizing MCF. It is helpful in achieving space-saving and high-density transmission lines.

*2 Mode field diameter (MFD) : MFD is one of the parameters of single-mode fibers. Although a light usually passes through the core region, in the case of single-mode fibers, it partially leaks into the cladding region. Therefore, the beam spot size is defined by MFD. MFD is an effective diameter calculated from the light power distribution. As MFD become smaller, the splice loss becomes sensitive to misalignment.

*3 Crosstalk : Crosstalk is a phenomenon where signals transmitted on one line leak into other lines. In this paper, we define it as leakage from one core to other cores of the MCF.

References

(1) T. Morioka, "New Generation Optical Infrastructure Technologies: "EXAT Initiative" Towards 2020 and Beyond", in Proc. OECC'09, FT4 (2009)
(2) T. Hayashi et al., "Ultra-low-crosstalk multi-core fiber feasible to ultra-long-haul transmission," in Proc. OFC2011, paper PDPC2 (2011)
(3) H. Takara et al., "1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) Crosstalk-managed Transmission with 91.4-b/s/Hz Aggregate Spectral Efficiency", in Proc. ECOC'2012, paper PDP Th.3.C.1 (2012)
(4) T. Saito et al., "Connection Techniques of Multi-Core Fiber," IEICE Society Conference 2011, BCS-1-3 (2011)
(5) R. Nagase et al., "Connection technique for Multicore Fiber," IEICE Technical Report vol. 112 no. 449 pp.1-4 (2013)
(6) O. Shimakawa et al., "Pluggable fan-out realizing physical-contact and low coupling loss for multi-core fiber," in Proc. OFC2013, OM3I.2 (2013)

Contributors (The lead author is indicated by an asterisk (*).)

O. SHIMAKAWA*
- Assistant Manager, Optical Communications R&D Laboratories

H. ARAO
- Optical Communications R&D Laboratories

M. SHIOZAKI
- Manager, Analysis Technology Research Center

T. SANO
- Ph.D.
  Manager, Optical Communications R&D Laboratories

A. INOUE
- General Manager, Optical Communication R&D Laboratories