Chapter 12

Novel MT/MPO Single-Mode Multifiber Connector Technologies for Optical Fiber Communications

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Additional information is available at the end of the chapter

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Abstract

This chapter reports the latest mechanically transferable (MT) and multifiber push-on (MPO) multifiber connector technologies. Low insertion-loss and high return-loss angled physical contact (APC)-MPO single-mode multifiber connectors are developed. For these multifiber connectors to achieve a high performance, it is necessary to reduce deviations of all components and to control fiber offset due to shear force caused by compressing two obliquely ended MT ferrules. MT single-mode 84-fiber connectors are developed to realize higher density multifiber connectors. We have developed a novel high-density optical cable joint that has a 24-connector array consisting of new 84-fiber MT connectors. The new cable joining technique significantly shortens the time needed to join the optical fiber cables. Novel optical fiber switches are developed on the basis of MT multifiber connector technology. The switches use a manual guide-pin slide method in special guide holes in a novel multifiber array. Because high precision multifiber connectors need to be measured and inspected, a new inspection technique for MT ferrules is developed and equipment for it is fabricated. The fabricated inspection equipment can measure MT ferrules with high speed, cost effectiveness, and high accuracy. These single-mode multifiber connectors can be used as key technologies for advanced optical fiber communication systems.

Keywords: optical connector, insertion loss, return loss, physical contact, fiber-to-the-home, data center

1. Introduction

The number of subscribers to broadband services in Japan now exceeds 38 million, and about 29 million subscribers were using fiber-to-the-home (FTTH) services as of September 2016 [1]. The FTTH networks use many various single-mode optical fiber connection technologies.

One such connection is a field mountable optical fiber connector (FMC) or field installable connector (FIC), and another type is a manufactured optical fiber connector. The mechanically transferable (MT) or multifiber push-on (MPO) connectors, which belong to the manufactured connectors, are particularly expected to be used in upcoming FTTH networks because these multifiber connectors are superior to single-fiber connectors with high-density optical fiber cable joints [2–6].

Optical fiber communication systems have been used in data centers in the USA. Multimode single-fiber connectors such as a little connector (LC) were mainly used previously, and multimode MPO connectors are also used in current data centers. In addition, high precision MPO connectors with single-mode fibers are expected to be used for communicating more information over long distances in huge data centers.

This chapter reports the latest MT/MPO multifiber connector technologies. Current MT/MPO connectors used in Japan and the USA are explained in Section 2, and our developed innovative single-mode multifiber connectors are reported in Section 3. The low insertion-loss and high return-loss angled physical contact (APC)-MPO single-mode multifiber connectors are described in Section 3.1. Next, MT single-mode 84-fiber connectors for realizing higher density multifiber connectors are explained in Section 3.2. Novel optical fiber switches based on MT multifiber connector technology are reported in Section 3.3. These connectors need to be measured and inspected for high precision multifiber connectors. In Section 4, a new inspection technique for MT ferrules and equipment using the technique are introduced. These single-mode multifiber connectors can be used as key technologies for advanced optical fiber communication systems.

2. Overview of MT/MPO multifiber connectors

Figure 1 shows the configuration of a typical FTTH network in Japan. It is mainly composed of an optical line terminal (OLT) in the central office, underground and aerial optical fiber cables, and an optical network unit (ONU) inside a customer's home and building. The network requires various fiber connections at office, outdoor, and home sites. With the fiber connections at aerial and home sites in particular, field installable connectors or field mountable connectors and mechanical splices are used to fit the best wiring depending on aerial conditions and room arrangement. Field assembly small (FAS) connectors and field assembly (FA) termination connectors are field installable connectors [7–9]. In contrast, manufactured connectors, such as miniature-unit (MU) coupling optical fiber and single-fiber coupling (SC) optical fiber connectors, are used in central offices and homes. MT connectors are also used in central offices for multifiber ribbon joints. MPO connectors are used in customers' buildings. These MT and MPO connectors are particularly expected to be used in the upcoming FTTH networks with high-density optical fiber cable joints.

Optical fiber communication systems have been used in data centers in the USA. Previously, multimode single-fiber connectors such as an LC connector were mainly used, and multimode MPO connectors are also used in current data centers. This is because multifiber

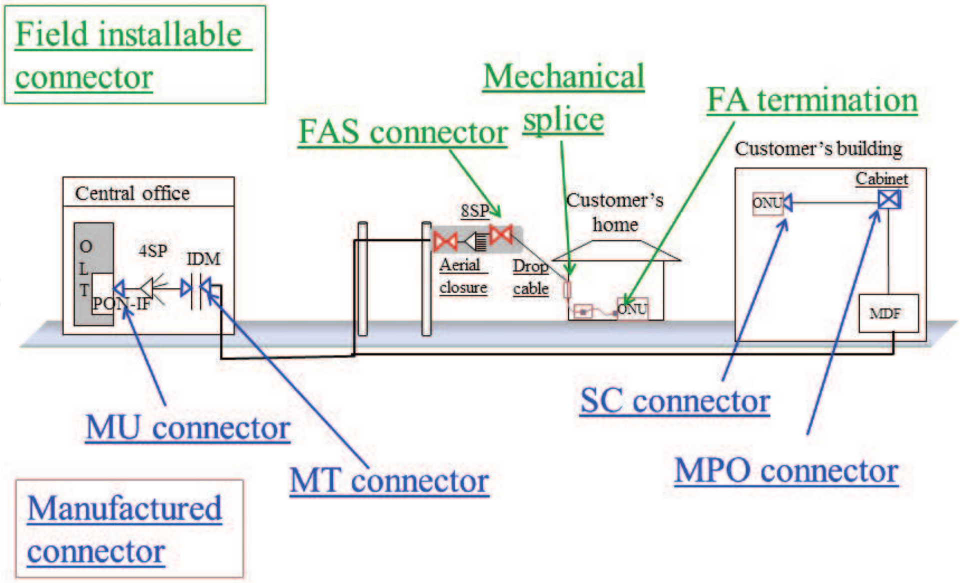
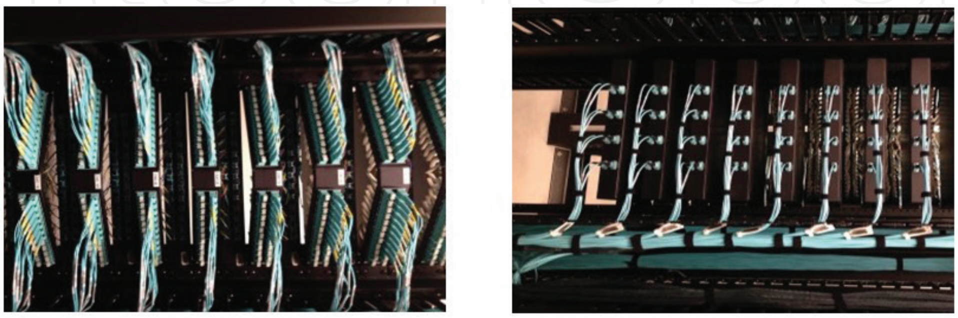


Figure 1. Typical FTTH network and various optical fiber connections.

connectors are superior to other single-fiber connectors with high-density optical fiber cable joints. **Figure 2** shows examples of optical fiber wiring (a) with LC single-fiber connectors and (b) with MPO multifiber connectors. Optical fiber wiring with the single-fiber connectors is slightly complicated, whereas that with the multifiber connectors is very simple and well ordered. The MPO multifiber connectors are consequently expected to be used in data center networks with high-density optical fiber cable joints. In addition, high precision MPO connectors with single-mode fibers are expected to be used for communicating more information over long distances in huge data centers. **Figure 3** shows the structure of the MT multifiber connector [2, 3], which consists of two plastic ferrules with two guide holes, two guide pins, and a clamp spring. The multifibers are positioned in a row between two guide holes. The ferrules are aligned by the two guide pins and two guide holes and then held with the clamp spring to achieve a low connection loss for multifiber ribbon connections. Refractive index matching material is used between the ferrule endfaces to reduce the



(a) (b)

Figure 2. Example of optical fiber wiring (a) with single-fiber connectors and (b) with multifiber connectors.

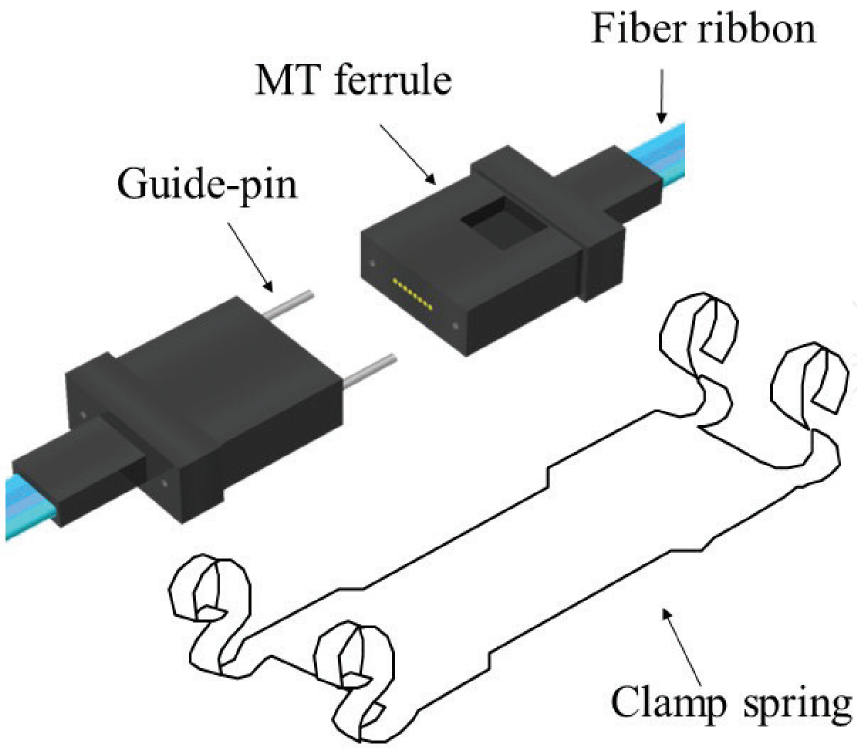


Figure 3. MT multifiber connector.

Fresnel reflection caused by an air-gap [10, 11]. The device is disconnected simply by removing the clamp spring and guide pins. The 4-, 8-, and 16-fiber MT connectors are currently used in the FTTH services in Japan.

Figure 4(a) shows the endface of an MT ferrule. In the MT ferrule endface, several fiber holes are positioned between two guide holes. The origin O is designated as the middle point of two guide hole centers. Each fiber hole is designed to be arranged with the designated fiber pitch on the basis of the origin. **Figure 4(b)** shows the fiber hole eccentricity of the MT ferrule. The actual fiber hole positions on the fabricated MT ferrule endface are different from the designated ideal positions because the molds are not perfectly accurate and/or plastic might deform during the MT ferrule fabrication. This large fiber hole eccentricity might result in large insertion loss of an MT connector, so it must be minimized for low insertion-loss MT connectors. Therefore, a technique has been developed to inspect for fiber eccentricities in MT ferrules, which is described in Section 4.

One application of the MT connector is as a multifiber push-on (MPO) connector [4–6, 12]. **Figure 5** shows the structure of the MPO connector, which is composed of two plugs and an adaptor. The plug contains an MT ferrule that has an endface that is obliquely polished with a slight fiber protrusion to enable physical contact. It is important for physical contact type connectors to eliminate an air gap between fiber ends [13–16]. Two guide pins are fitted into two guide holes in one ferrule to align the ferrules. The plug and adaptor are engaged by fitting a pair of elastic hooks into corresponding grooves. This connector provides easy push-pull reconnections without the need for refractive index matching material.

Figure 6 shows the fabrication process of an MPO plug. First, the mold is fabricated by using high precision mechanical engineering. A high precision mold is used, and an MT ferrule is

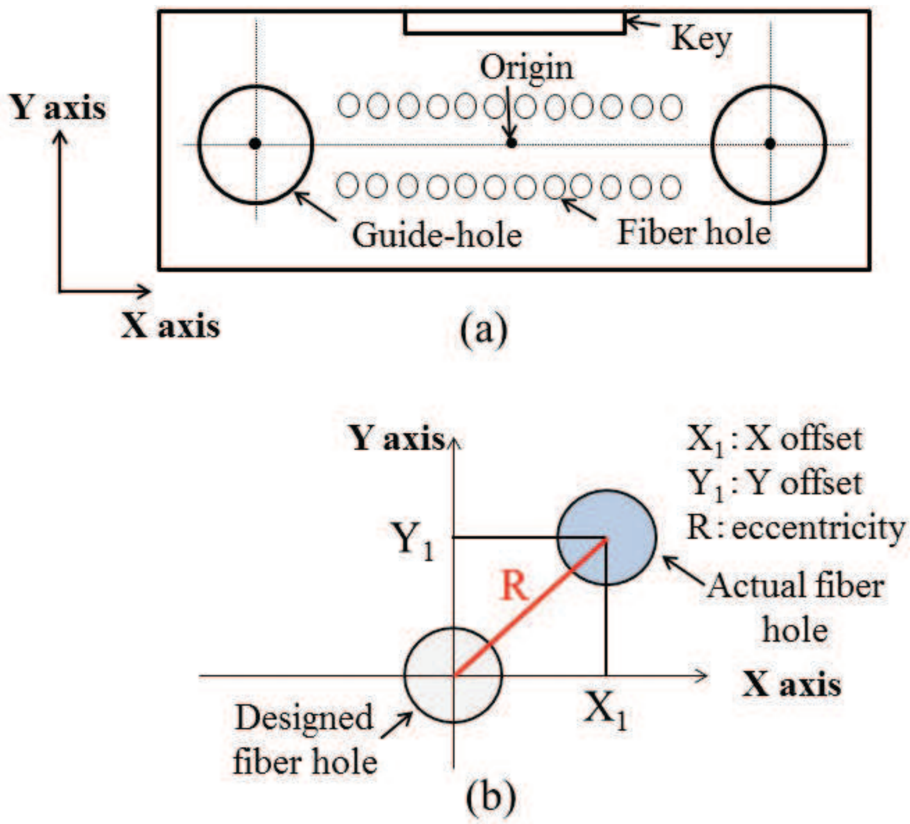


Figure 4. (a) Endface and (b) fiber hole eccentricity of MT ferrule.

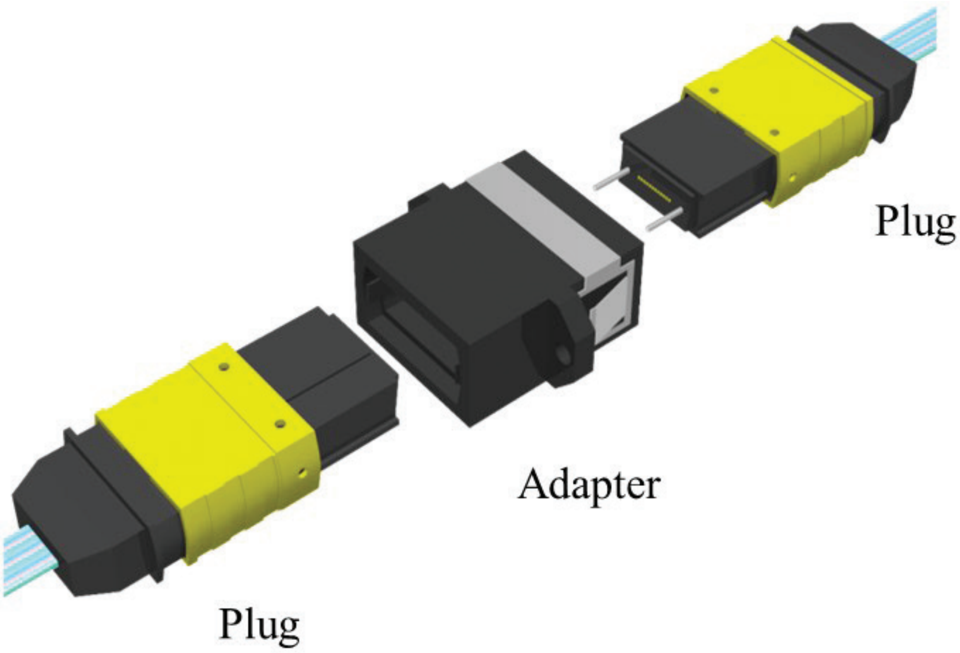


Figure 5. MPO multifiber connector.

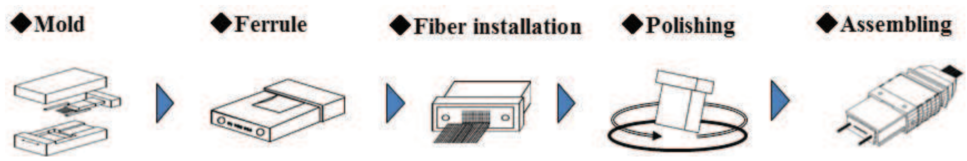


Figure 6. Fabrication process of MPO plug.

fabricated from plastic resin. This MT ferrule is a key device for MT/MPO connectors. Next, the multifiber ribbon is installed and fixed with adhesive in the MT ferrule. The MT ferrule containing the multifiber ribbon is then obliquely polished. Finally, an MPO plug houses the obliquely ended MT ferrule with multifibers. This MPO fabrication process contains two steps: ferrule making and connector assembling. Currently, fewer than 10 companies make ferrules, but more than 100 companies assemble connectors. More companies will make ferrules and assemble connectors in the future.

3. Innovative multifiber connectors based on MT/MPO connectors

This section reports our innovative multifiber connectors based on MT/MPO connector technologies. **Figure 7** shows three target single-mode multifiber connectors. The first is an extremely lower insertion-loss multifiber connector, which is detailed in Section 3.1. The second is a higher density multifiber connector that enables two high-density optical fiber cables to be connected as soon as possible, which is explained in Section 3.2. The third is a functional multifiber connector that enables multifibers to be switched, which is described in Section 3.3.

3.1. Lower insertion-loss multifiber connectors

We have investigated extremely great performances of multifiber connectors and developed angled physical contact (APC) MPO connectors that have an insertion loss lower than 0.2 dB and return loss higher than 60 dB. This section explains these APC-MPO connectors. To create lower insertion-loss connectors, fiber core offsets from the ideal positions must be decreased. APC-MPO connectors have two types of fiber core offset. One is due to deviation of components and the other is due to shear force caused by compressing two obliquely ended MT ferrules. These two fiber core offsets are detailed below.

Optical loss in a fiber connection has four causes: fiber-core offset, fiber-axis tilt, fiber-end separation, and mode field mismatch [17, 18]. With MT connectors, fiber-core offset is the dominant factor generating optical loss, and so we have limited our considerations to this factor. **Figure 8** shows four deviations: d_1, d_2, d_3, and d_4. d_1 is the fiber hole position deviation. d_2 is the deviation due to the clearance between a fiber and a fiber hole. d_3 is the deviation due to the clearance between a guide pin and a guide hole. d_4 is the fiber-core eccentricity [19]. The four deviations dependently affect total fiber core deviation. To realize an insertion loss of lower than 0.2 dB, the total deviation must be less than 0.5 μm.

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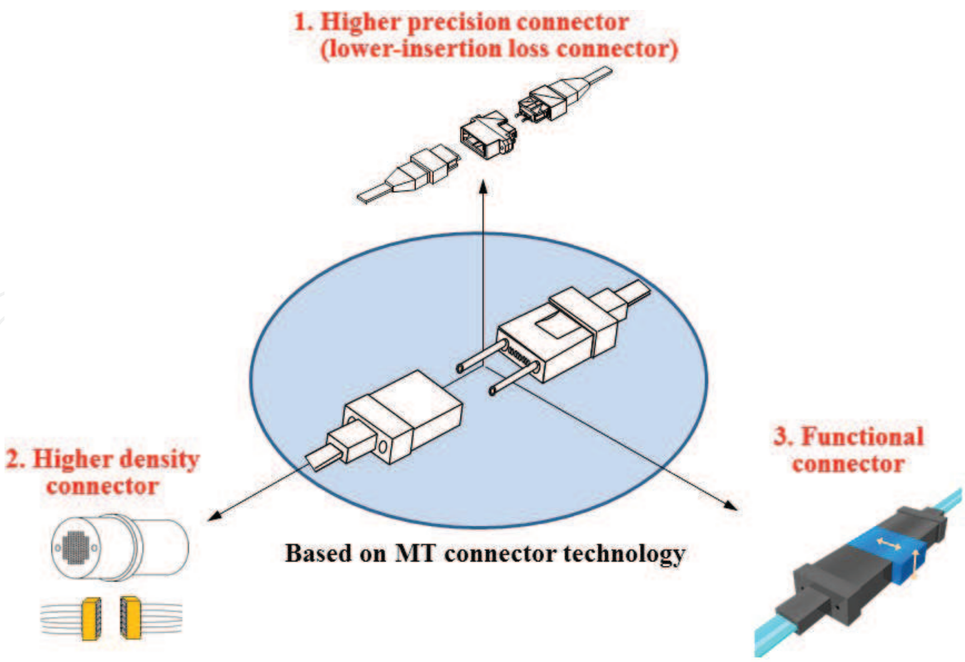

Figure 7. Three targets of single-mode multifiber connector technologies.

Figure 9(a) and **(b)** shows side views of connected MT ferrules and an MT ferrule endface in an MPO plug. The MPO connector uses MT ferrules obliquely polished at 8 degrees and can provide high return-loss characteristics. In contrast, the shear force occurs in the connected obliquely ended MT ferrules when two MT ferrules are compressed. This shear force leads to the Y offset of connected fibers in the MT ferrule. By considering the Y offset, fiber positions are designed to be previously offset, as shown in **Figure 9(b)**. This offset quantity is dependent on clearance between a guide hole and a guide pin and deformed material of an MT ferrule. The fiber offset must be controlled for low insertion-loss MPO connectors.

On the basis of the above design, we fabricated three pairs of high precision single-mode 12-fiber APC-MPO connectors by using three different fabrication molds. The fabricated APC-MPO connectors used high precision ferrules with d_1 of less than 0.5 μm and severely

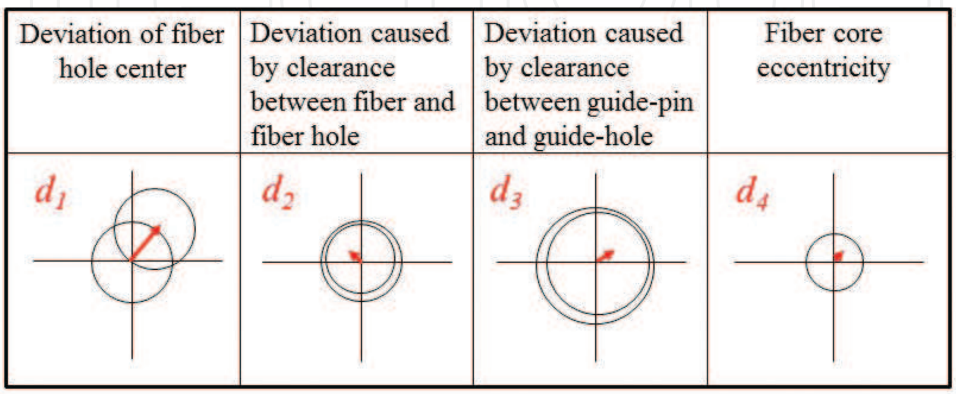

Figure 8. Four deviations resulting in fiber core offset.

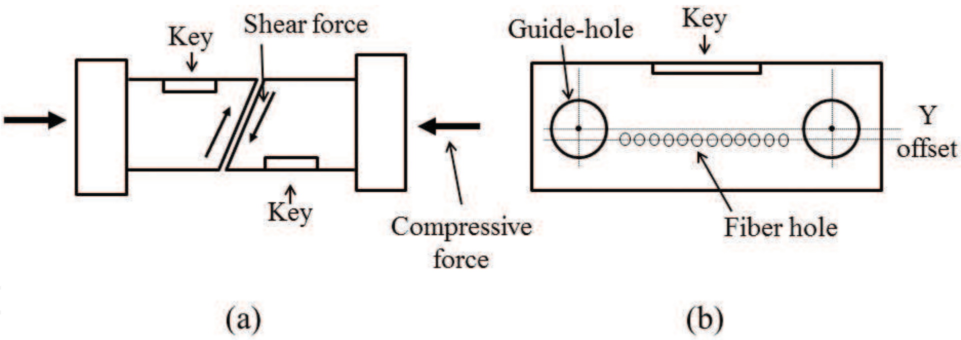

Figure 9. (a) Side view of connected MT ferrules and (b) MT ferrule endface in MPO plug.

controlled guide pins and optical fibers with lower d_2, d_3, and d_4. The fabricated APC-MPO connectors also used the controlled Y offset quantity. We measured the insertion losses and return losses using 1.31 μm LD, a power meter, and a backreflection meter. **Figure 10** shows histograms of the insertion losses and return losses of the connectors. The average insertion loss was 0.08 dB with a maximum of 0.17 dB. The return losses were greater than 64 dB. Consequently, we have revealed that the fabricated APC-MPO has an excellent performance.

3.2. Higher density multifiber connectors

We have developed a higher density multifiber connector to enable two high-density optical fiber cables to be connected as soon as possible [20–23]. **Figure 11(a)** and **(b)** shows the novel high-density preconnectorized cable joint and endface of high-count fiber MT connectors, respectively. The cable joint consists of an arrayed high-count fiber MT connector and a cable joint housing and can connect high-density optical fiber cables such as 2000-fiber cables at one time. When it is connected, each MT connector is aligned with two guide pins and pushed toward the opposite ferrule by a spring. The MT connectors are aligned and connected individually. This structure is the same as those of a conventional MT connector and MPO connector. The connector endface is polished at a right angle. The connectors need an index matching material to eliminate the Fresnel reflection caused by an air gap. We used a conventionally sized 2.5-mm-thick MT ferrule that has guide holes of 4.6 mm in pitch and 0.7 mm in diameter.

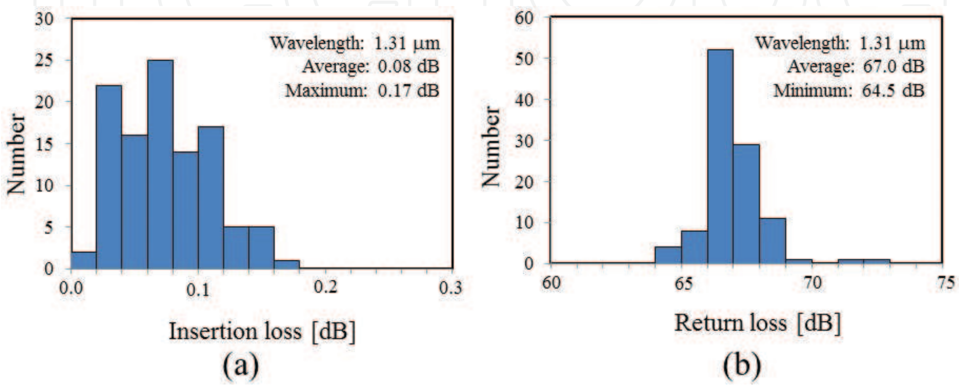

Figure 10. (a) Insertion loss and (b) return loss of fabricated high precision APC-MPO connectors.

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This is because this type of ferrule is utilized widely in optical cable components such as MPO connectors. The optical fiber ribbons are generally installed into fiber holes of a ferrule. We used a conventional 12-fiber ribbon with a 0.3 thickness and 0.25 fiber pitch to assemble our fabricated connector. By considering the thickness of the fiber ribbon and that of the MT connector ferrule, we figured that seven is the maximum number of fiber ribbons installable in an MT ferrule. Therefore, we decided that 84 (7 rows of 12) is the target number of fibers installed in our high-count fiber MT connector as shown in **Figure 11(b)**.

On the basis of the above design, we fabricated an 84-fiber MT connector and high-density preconnectorized cable joint for 2000 fiber cables. **Figure 12(a)** and **(b)** shows endface photographs of the fabricated high-count fiber MT connector and high-density preconnectorized cable joint, respectively. The high-count fiber MT connector ferrule consists seven rows of 12 fiber ends between the two guide holes and the high-density preconnectorized cable joint has a 4 × 6 array of a high-count 84-fiber MT connector. Consequently, the fabricated high-density preconnectorized cable joint can potentially connect 2016 fiber cables at one time.

The fabricated high-count 84-fiber MT connector was measured at a wavelength of 1.31 μm. We connected six pairs of high-count fiber MT connectors using the same cramp spring as the conventional MT connectors. The average and maximum insertion losses were 0.40 and 1.8 dB, which are slightly larger than the average (0.3 dB) and maximum (1.0 dB) of the conventional 8-fiber MT connectors. This is because the fabricated fiber hole positions of 84-fiber MT ferrules are thought to have a large offset from the designed positions. However, we think that these offsets can be decreased with the same precision as with the conventional MT connector. The assembly of the high-density preconnectorized cable joint must not generate any excess loss. We demonstrate the insertion-loss changes of the 84-fiber MT connectors in the center and the corner of the installed cable joint. **Figure 13(a)** and **(b)** shows the measured insertion-loss change of the high-count 84-fiber MT connectors located at the center and corner of the cable joint, respectively. In **Figure 13**, there is no loss change of the high-count fiber MT connector before and after assembly. Consequently, there turned out to be no excess loss in the cable joint. Although it takes about 20 hours to connect two sets of

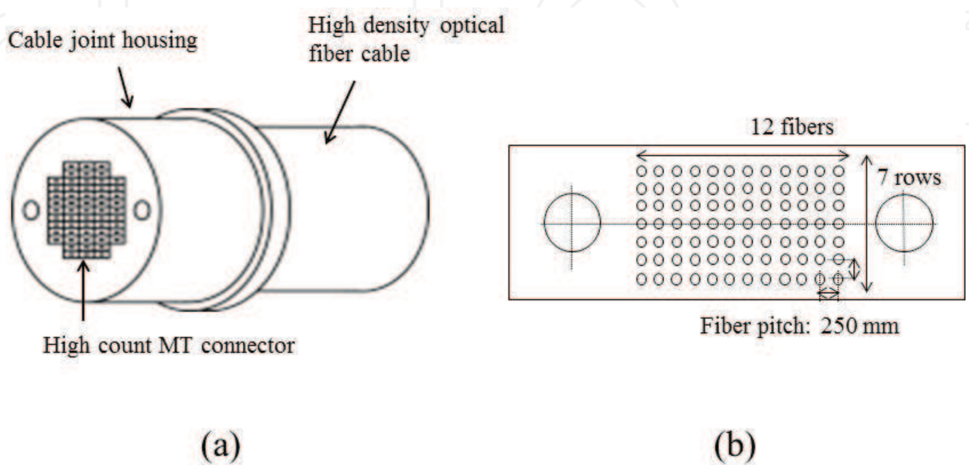

Figure 11. (a) High-density preconnectorized cable joint and (b) high-count fiber MT connector.

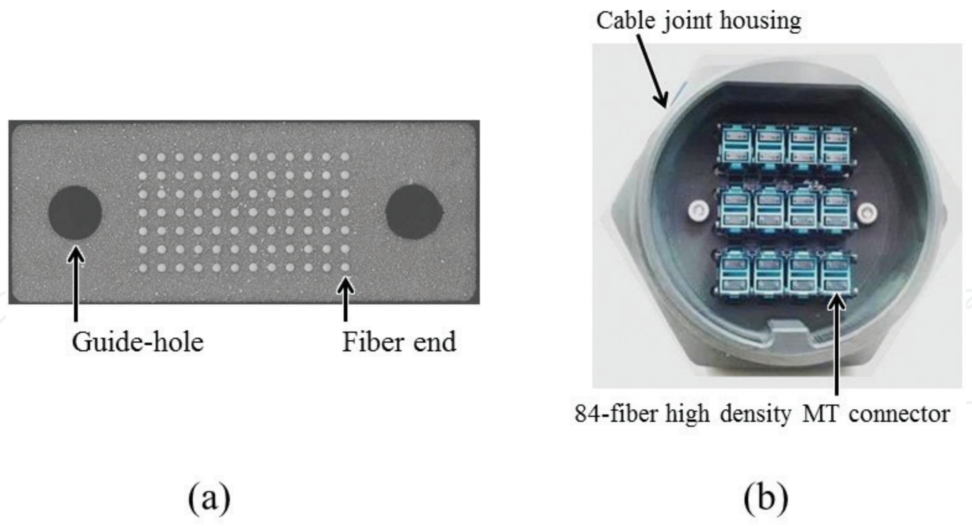

Figure 12. Endface pictures of (a) fabricated high-count fiber MT connector and (b) high-density preconnectorized cable joint.

2000 single-mode optical fiber cables using a fusion splice, it took about 5 minutes to connect two sets of 2000 single-mode optical fiber cables using the fabricated cable joint. The cross-sectional area of the cable joint was less than one-fifth that of a conventional optical closure. We have found that the fabricated cable joint can significantly reduce the time and space needed to join high-density optical fiber cables.

3.3. Functional multifiber connector for switching fibers

We have designed new kinds of functional multifiber connectors on the basis of MT connector technologies [24]. One is a device for switching fibers [25], which is described in this section. Figure 14 shows the basic structure and the switching mechanism of the proposed

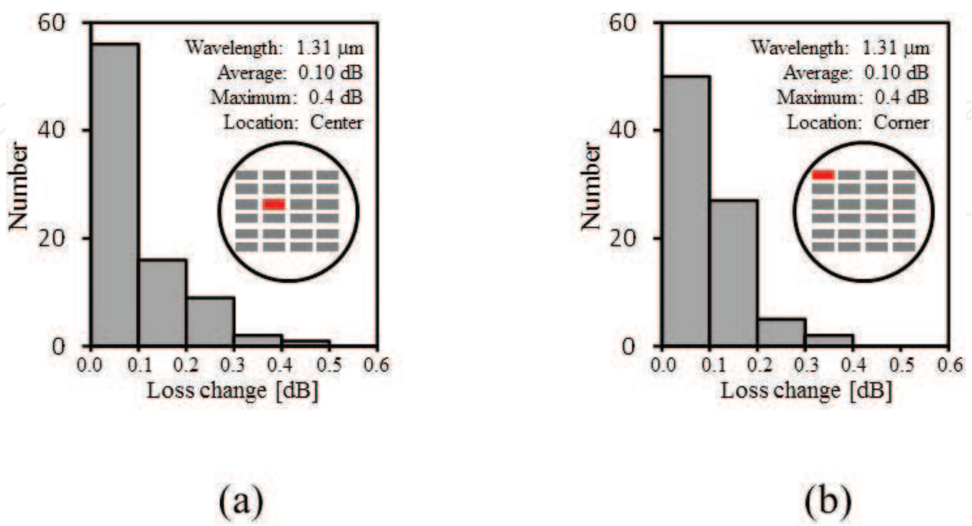

Figure 13. Measured insertion-loss change of the high-count 84-fiber MT connectors located at (a) center and (b) corner of cable joint.

switch. **Figure 14(a)–(c)**, respectively, shows the fiber connection states before, during, and after switching from one fiber to another. First, two guide pins are fixed at the bottom of the guide holes with the elastic materials in the multifiber array, as shown in **Figure 14(a)**. Next, when the conventional MT ferrule is pushed up with a certain force in a perpendicular direction, the two guide pins begin to slide in the same direction because the elastic materials change to the horizontal direction, as shown in **Figure 14(b)**. Finally, two guide pins are fixed at the top of the guide holes in the multifiber array by the restored elastic materials again after two guide pins have finished sliding, as shown in **Figure 14(c)**. Consequently, a certain optical fiber in the conventional MT ferrule can be switched from one optical fiber to another in the multifiber array.

We discuss the various applications of the proposed optical switch. **Figure 15** shows four types of switches. Types a and b are based on the conventional MT ferrule and multifiber array. In type a, two guide pins slide parallel to the multifiber arrangement between two guide holes. With this switch, a fiber from a row in the MT ferrule can be switched from one optical fiber to another in the same row in the multifiber array. In type b, two guide pins slide vertically in relation to the multifiber arrangement with two rows. In this switch, the optical fibers can be switched by the unit of the row. Type c can be inserted and removed between the two endfaces of conventional MT ferrules. With this switch, two guide pins can slide either parallel or vertical to the multifiber arrangement. This switch can be applied to conventional MT connectors and is useful both for installing MT connectors and for existing MT connectors in current optical fiber systems. Type d is an insertion and removal switch in which two guide pins slide vertically in relation to the multifiber arrangement. Therefore, the optical fibers are switched by the unit of the MT ferrule. Consequently, by using the proposed switching method where two guide pins slide in special guide holes, various types of switches with multifiber arrays can be realized for various uses.

We fabricated types a and c for an optical switch. The structure and performances of the type-a optical fiber switch are described elsewhere [25]. This section explains the type c optical fiber

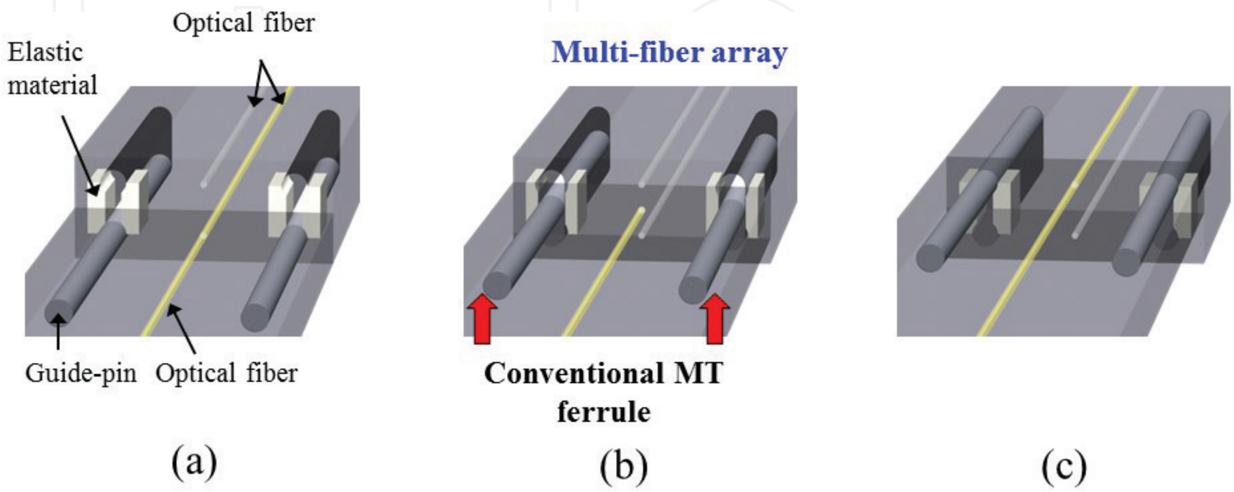

Figure 14. Basic switch structure and the switching mechanism (a) before, (b) during, and (c) after switching.

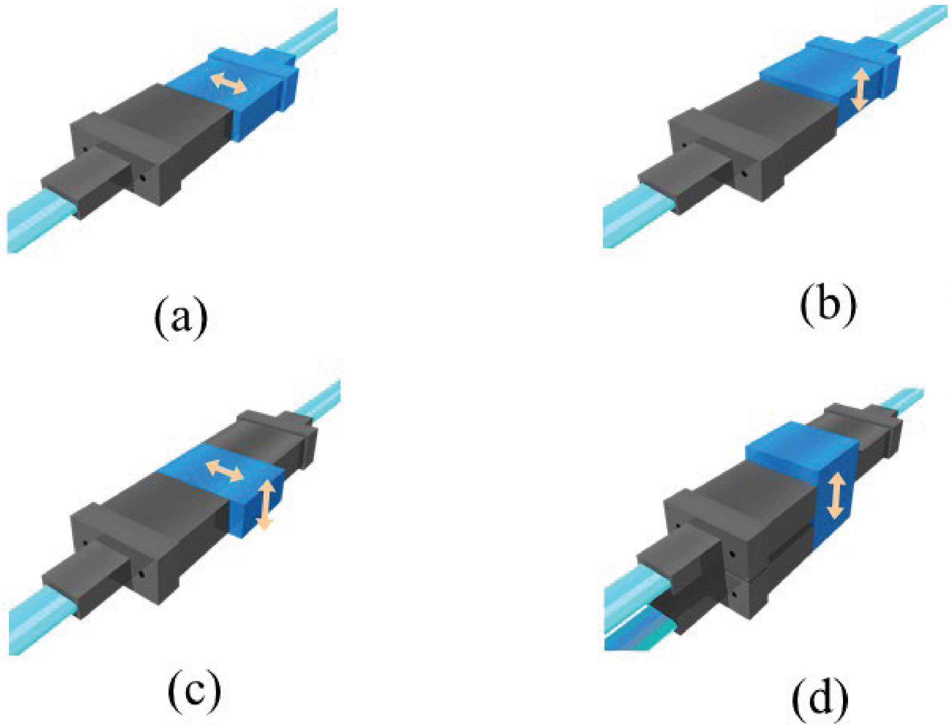

Figure 15. Various types of switches. (a) Fiber switch in a row, (b) fiber row switch, (c) insertable and removable switch, and (d) MT ferrule switch.

switch. **Figure 16(a)** and **(b)** shows the structure and a photograph of the fabricated multifiber-ribbon switch, which is composed of two MT ferrules and a multifiber array. The multifiber array has a novel guide hole structure in which two guide pins slide vertically to the four-fiber arrangement. The MT ferrules have two rows of four fibers. **Figure 17** shows the switching mechanism. In condition A before switching (a), the upper fiber ribbon in MT ferrule 1 is connected to optical fibers in the multifiber array and is also connected to the upper fiber ribbon in MT ferrule 2. When MT ferrule 1 is pushed up manually with a certain force in a perpendicular direction, the two guide pins slide in the opposite direction. In condition B after switching (b), where two guide pins in the multifiber array slide to the 0.25 mm length vertically to the arrangement direction, the lower fiber ribbon in MT ferrule 1 is connected to optical fibers in the multifiber array and is also connected to the upper fiber ribbon in MT ferrule 2. Therefore, the upper fiber ribbon in MT ferrule 1 is switched to the lower fiber ribbon in MT ferrule 1.

We measured the connection losses of the fabricated multifiber-ribbon switch at a wavelength of 1.3 μm using an LD and an optical power meter. The conventional two MT ferrules and multifiber array are connected with all four guide pins and a special clamp spring. Refractive index matching material is used between the ferrule and the multifiber array endfaces (both connections 1 and 2). **Figure 18** shows the measured connection losses. The average connection loss is 1.1 dB. These connection losses are higher than those of the conventional MT connectors because the fabricated fiber positions are thought to have large misalignments of the offset from the designed positions. However, we think that these offset misalignments can be minimized with the same precision as with the conventional MT connector. We also measured

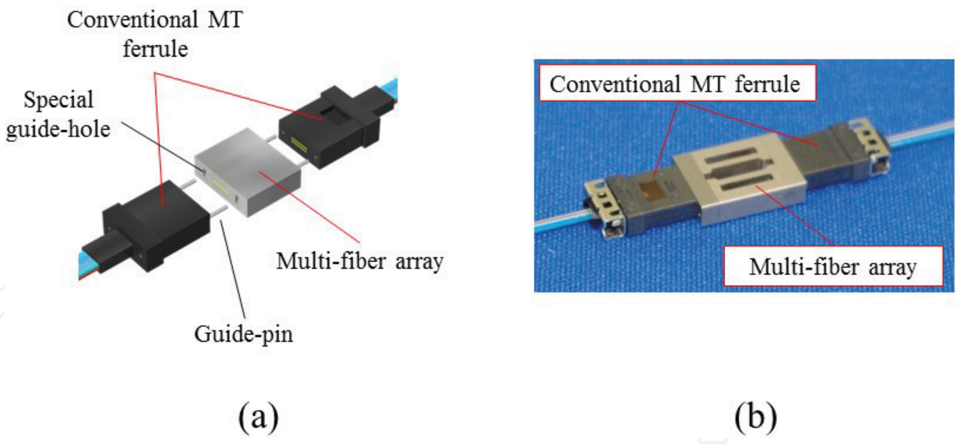

Figure 16. Fabricated fiber-ribbon switch. (a) Structure and (b) photograph of insertable and removable switch.

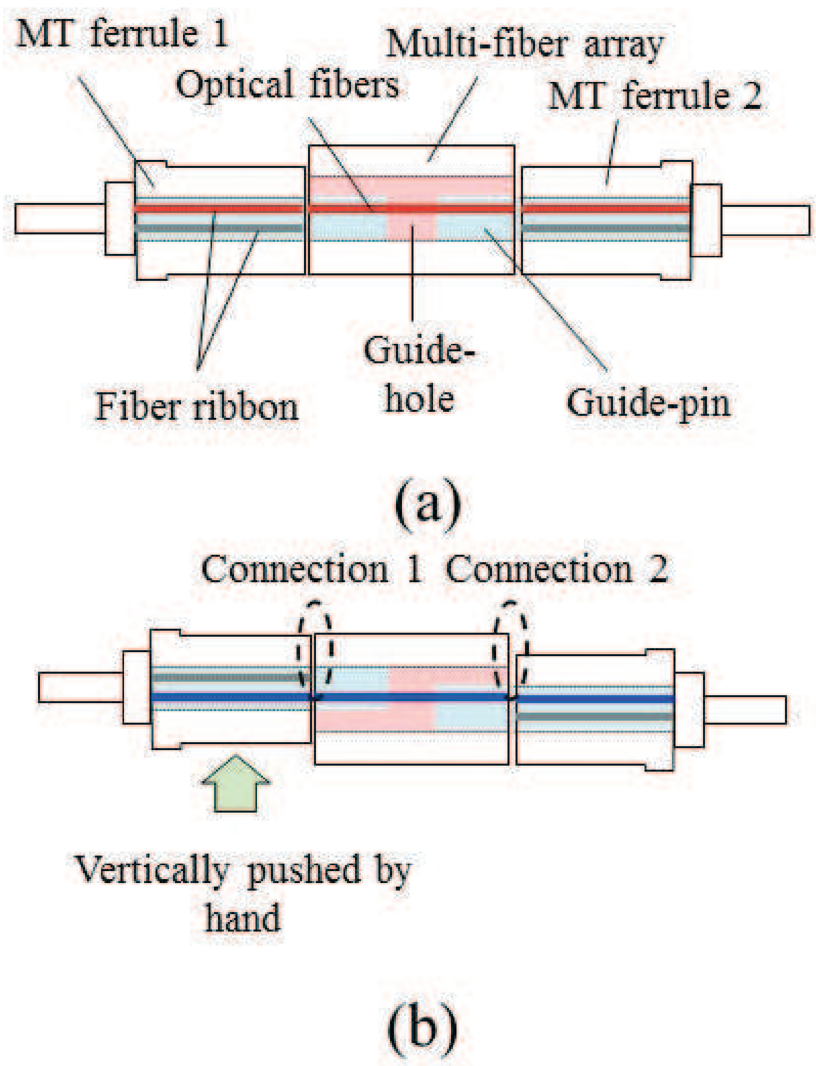

Figure 17. Switching mechanism of fiber-ribbon switch. (a) Before switching (condition A) and (b) after switching (condition B).

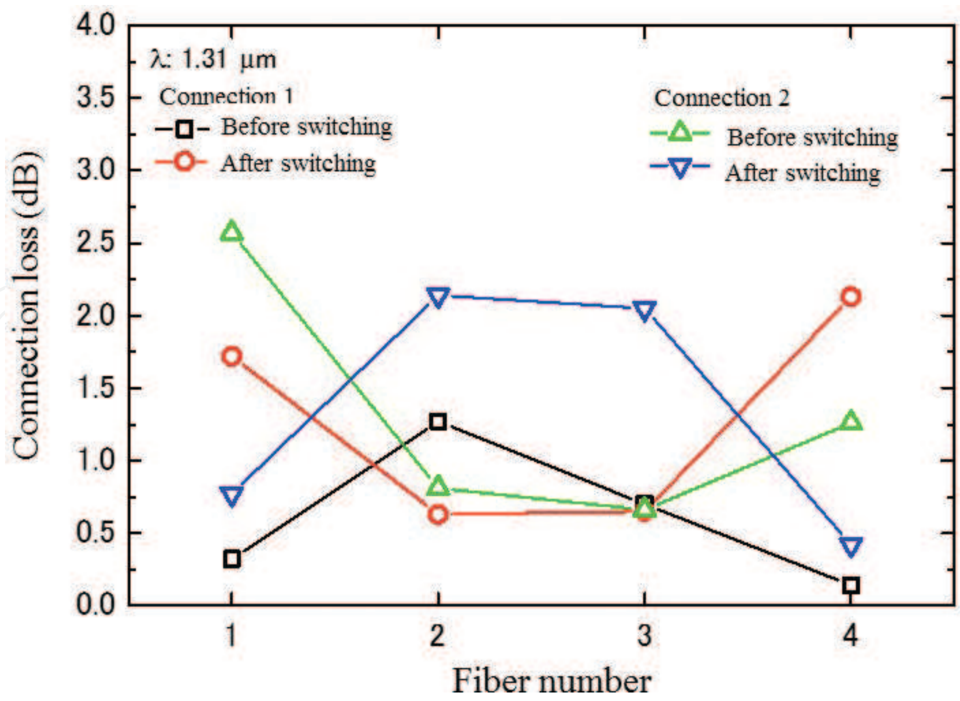

Figure 18. Connection losses of fabricated fiber-ribbon switch.

the force needed to push the conventional MT ferrule or multifiber array by hand in order to switch fibers. The measured forces were about 9.5 N. Consequently, we revealed that the fabricated switch can provide ease of handling.

4. Novel inspection technique for MT ferrule

To fabricate a high precision multifiber connector, MT ferrules need to be inspected. To shorten the time it takes to measure MT ferrules using conventional inspection equipment, we have created a novel inspection technique that has both fast measurement and low cost features. This section describes the new inspection technique.

Figure 19 shows the **(a)** structure and **(b)** observation area of conventional inspection equipment for MT ferrules [26]. The conventional equipment consists of a light source, high precision sample stage, an objective lens with 20 times, a charge-coupled device (CCD) camera with 0.4 M pixels, an image processor, and a computer. As shown in **Figure 19 (b)**, the observation area of conventional equipment is 0.2 × 0.17 mm, which corresponds to covering area of a fiber hole. To inspect whole fiber holes and two guide holes on an MT ferrule, the MT ferrule sample must be scanned on the high precision sample stage. Therefore, the conventional inspection equipment takes a long time to measure MT ferrules. We have thus designed and fabricated new inspection equipment to shorten the measurement time.

Figure 20 shows the **(a)** structure and **(b)** observation area of new inspection equipment for MT ferrules [27]. The novel equipment consists of a light source, an objective lens with 1 time, a CCD camera with 10 M pixels, an image processor, and computer. To reduce measurement

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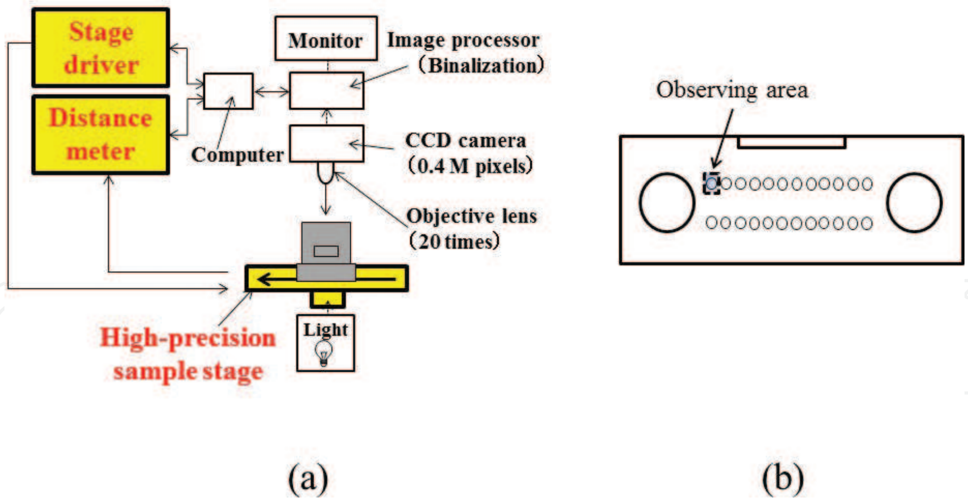


Figure 19. (a) Structure and (b) observation area of conventional inspection equipment for MT ferrules.

time, the scanning measurement must be eliminated. Therefore, the objective lens is changed from the conventional 20-time lens to a 1-time lens. Consequently, the observation area is expanded to be covered by the whole endface of an MT ferrule: 6.4 × 4.6 mm. In addition, the new inspection equipment is given a simpler structure and made more cost effective by eliminating the conventional high precision sample stage.

Our goal is to give the new inspection equipment the same measurement accuracy as the conventional equipment: less than 0.1 μm. The measurement accuracy of the new inspection equipment generally worsens because the objective lens is changed. To improve this worsened measurement accuracy, two methods were used. One is to change the pixels of the CCD camera and the other is to use multivalue processing with an image processor.

Figure 21 shows a photograph of the fabricated inspection equipment for MT ferrules. The fabricated inspection equipment is simpler and more cost-effective because it does not need a high precision sample stage, a stage driver, or a laser distance meter. We have experimentally demonstrated the multivalue processing using an image processor. **Figure 22** shows

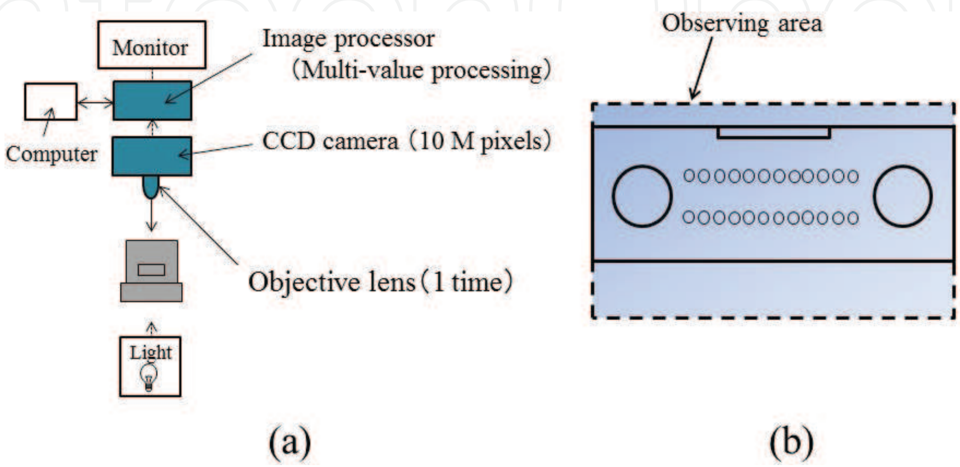


Figure 20. (a) Structure and (b) observation area of novel inspection equipment for MT ferrules.

experimental results for measurement time and accuracy for a 24-fiber MT ferrule. The measurement accuracy is the standard deviation of nine measurements. As the multivalue with the image processor becomes larger, the normalized standard deviation decreases whereas the normalized measurement time increases. These results indicate that there are optimal conditions for both high speed and high accuracy measurement. **Figure 23** shows measured fiber hole offsets for the same 24-fiber MT ferrule using the conventional and the fabricated inspection equipment. The offset results for the conventional and fabricated equipment are almost the same. The measured accuracy with the fabricated inspection equipment is less

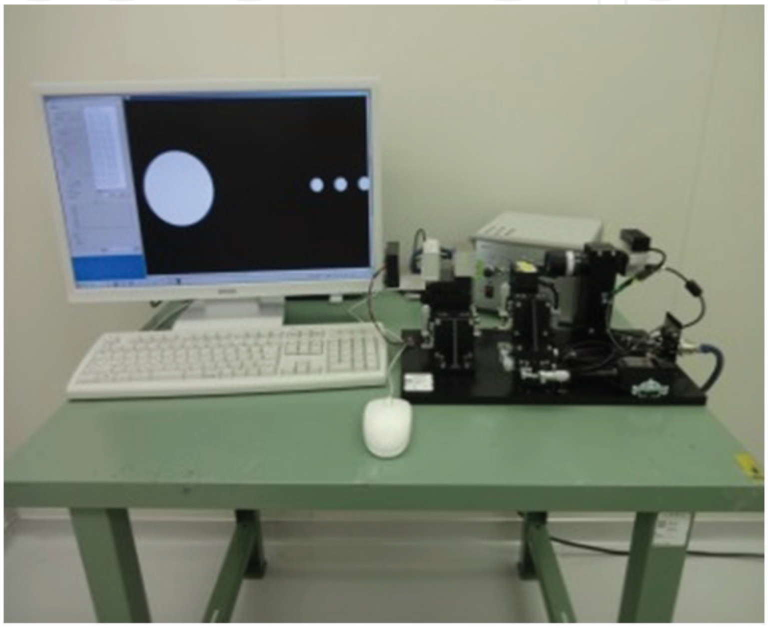


Figure 21. Photograph of the fabricated inspection equipment for MT ferrules.

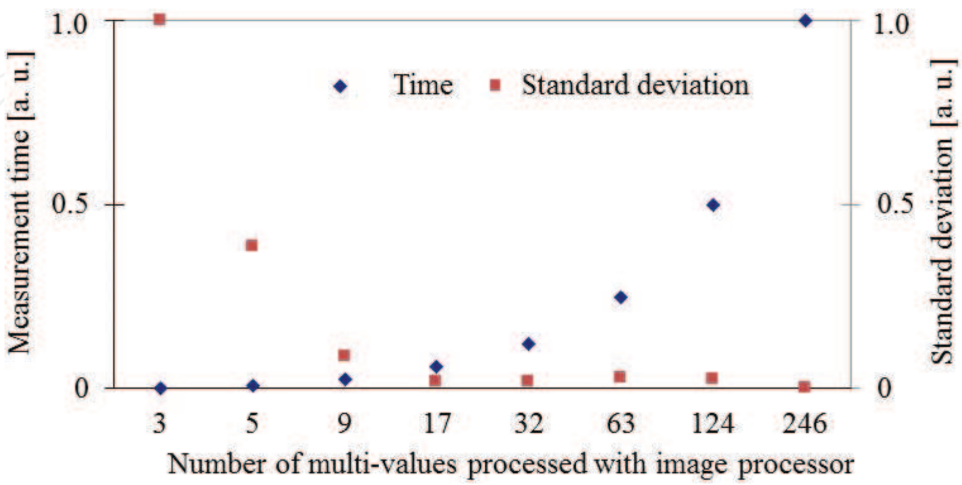
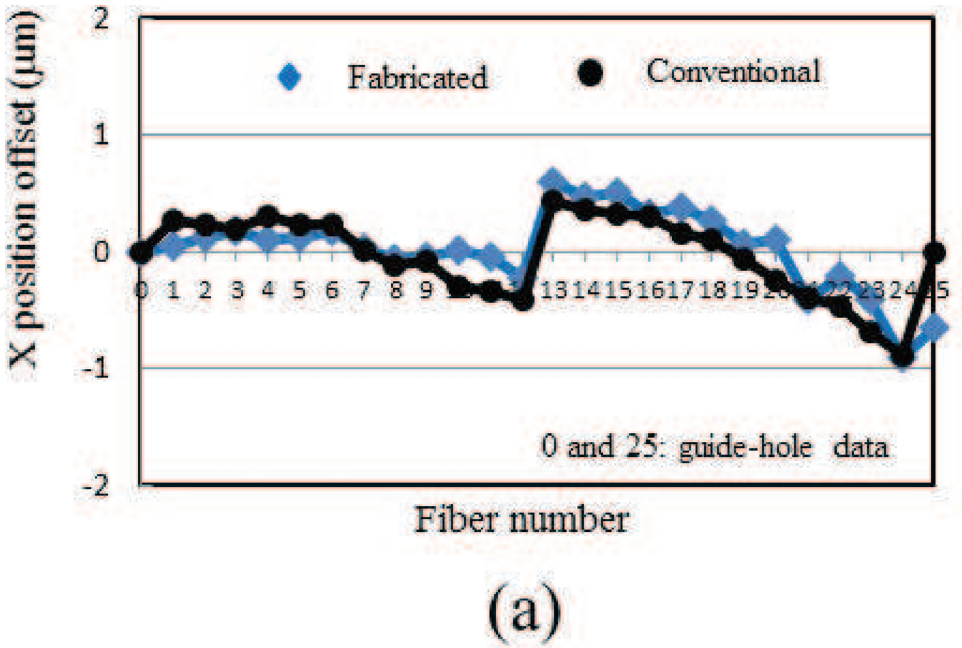


Figure 22. Experimental results of measurement time and accuracy to 24-fiber MT ferrule.



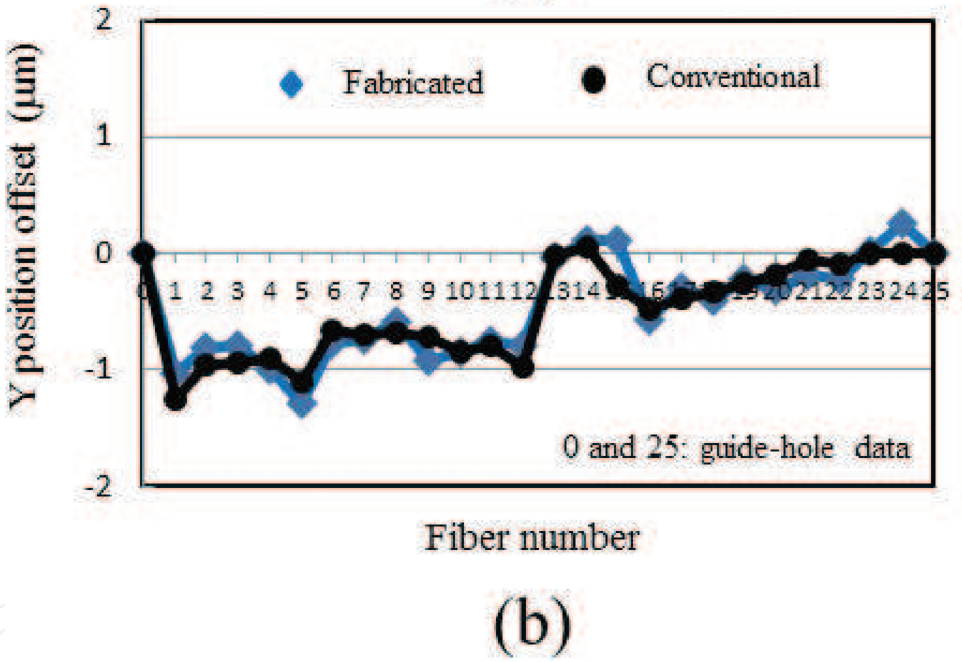


Figure 23. Measured fiber hole offsets of same 24-fiber MT ferrule using the conventional and fabricated inspection equipment. (a) X position offset and (b) Y position offset.

than 0.1 μm, which is as good as that of the conventional inspection equipment. It takes 3 minutes 40 seconds and 11 minutes 30 seconds to measure 24-fiber and 84-fiber MT ferrules using the conventional inspection equipment, respectively. In contrast, it takes 10 seconds each to measure 24-fiber and 84-fiber MT ferrules using the fabricated inspection equipment. Consequently, we reveal that the fabricated inspection technique can measure MT ferrules with high speed, cost effectiveness, and high accuracy.

5. Conclusion

This chapter reported the latest mechanically transferable (MT) and multifiber push-on (MPO) multifiber connector technologies.

Low insertion-loss and high return-loss angled physical contact (APC)-MPO single-mode multifiber connectors were developed. For these multifiber connectors to achieve a high performance, it is necessary to reduce deviations of all components and to control fiber offset due to shear force caused by compressing two obliquely ended MT ferrules.

Next, MT single-mode 84-fiber connectors were developed to realize higher density multifiber connectors. We have developed a novel high-density optical cable joint that has a 24-connector array consisting of new 84-fiber MT connectors. The new cable joining technique significantly shortens the time needed to join the optical fiber cables.

Novel optical fiber switches were developed on the basis of MT multifiber connector technology. The switches use a manual guide-pin slide method in special guide holes in a novel multifiber array. The fabricated fiber switches can be easily pushed up at a force of less than 10 N by hand.

Because high precision multifiber connectors need to be measured and inspected, a new inspection technique for MT ferrules was developed and equipment for it was fabricated. The fabricated inspection equipment can measure MT ferrules with high speed, cost effectiveness, and high accuracy.

These single-mode multifiber connectors can be used as key technologies for advanced optical fiber communication systems.

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