INVITED PAPER *Joint Special Section on Opto-electronics and Communications for Future Optical Network*

Optical Fiber Connector Technology

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SUMMARY Various optical fiber connectors have been developed during the 40 years since optical fiber communications systems were first put into practical use. This paper describes the key technologies for optical connectors and recent technical issues.

key words: *optical connector, telecommunication, single-mode fiber, multicore fiber, hollow-core fiber*

1. Introduction

The expansion of optical telecommunication networks and data center systems requires a large number of optical fiber connectors. These optical connectors for single-mode fiber (SMF) need a precise alignment mechanism with a repeatable accuracy of better than 1 μm. They are unique among optical components in that they require resistance from an external force. Although they must usually allow component deformation of around tens of microns, an accuracy of better than 1 μm is required. Moreover, they should also offer long-term reliability and be inexpensive [1].

The basis for optical connector technologies was established between 1980 and 2000. In the 1980s, the first optical trunk line was launched and began to expand rapidly. In 2001, the first commercial fiber-to-the-home (FTTH) service for ordinary users was launched in Japan [2]. In the same era, we also experienced a big change in the telecommunication system, from telephone to internet. In this era, the rapid improvement of optical network systems and data center systems required improved optical connectors. Optical network and data center systems have continued to grow since the year 2000 and they require new fiber-optic interconnect technologies.

Even with such progress, the principle and basic structure of the optical connector have not changed. Over the past 30 years, single-fiber coupling connectors have used zirconia ferrules and split sleeves, multifiber connectors have used mechanically transferable (MT) ferrules and both connector categories have used physical contact (PC) technologies because they provide excellent performance at a low cost. The PC technologies for constructing optical networks have been recognized as mainstream technologies for more than 35 years since they were introduced into the market and were awarded IEEE Milestone status in 2021.

The SMF currently used as the widest band medium has a theoretical limit of 100 Tb/s per fiber, and if the demand for traffic continues to increase, there is a concern that a capacity crunch will occur in the near future. Research on multicore fibers (MCFs) and hollow-core fibers (HCFs) is in progress to develop technologies that exceed this limit. Research on optical connectors for these new structures is also under way.

This paper describes the fundamentals underlying optical connectors and provides a brief history of optical connector improvements including recent progress.

2. Fundamentals of Optical Connectors

There are two types of optical connectors used in telecommunication networks: single-fiber coupling connectors and multifiber coupling connectors. In telephone offices, the former are mainly used and they are operated frequently and require excellent repeatability, and the latter, including those installed in outside plant [3], are usually operated during optical network construction and transfer splicing. Both types are used in data center systems, and they are usually operated during system construction, which requires the highest density packaging. Different key technologies have been developed and improved for both types of connectors.

A. Single-fiber coupling connectors
Single-mode fiber optical connectors require an attenuation of less than 0.5 dB and a return loss of 40 dB or more. To realize these requirements with the butt joint mechanism, the fiber core offset should be less than 1 μm. Four conditions (a)–(d) must be met to achieve this requirement as shown in Fig. 1. The results for each condition are also shown in Fig. 1.

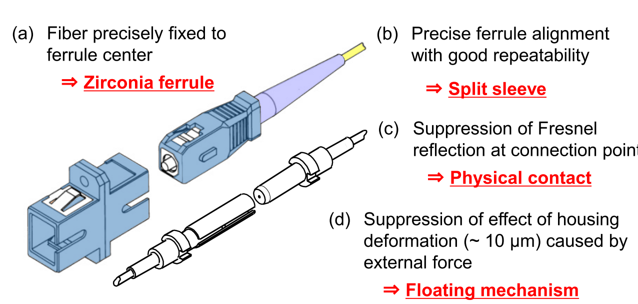

Fig. 1 Four conditions of single-fiber coupling connectors.

Manuscript received January 5, 2023.
Manuscript revised April 4, 2023.
Manuscript publicized May 11, 2023.
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DOI: 10.1587/transcom.2022OBI0002

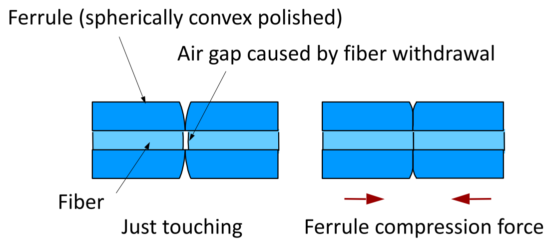

Fig. 2 Fundamentals of physical contact technology.

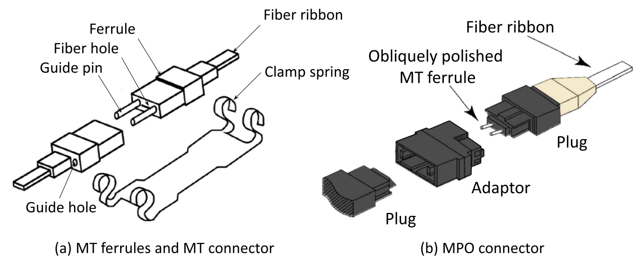

Fig. 3 Multifiber connector.

Low-cost zirconia ferrule manufacturing technology has been established for single-mode simplex connectors [4]. This is a way of meeting the precise fiber fixing condition (a). A split sleeve was also developed to realize precise ferrule alignment with good repeatability (b). The connection repeatability was improved using zirconia split sleeves [5]. To suppress the Fresnel reflection at the connection point, the ferrule endfaces are polished to provide them with a spherically convex shape and thus allow physical contact (PC) to be realized between two fiber ends as shown in Fig. 2(c) [6], [7]. The fiber-to-fiber contact cannot be maintained solely by bringing the polished ferrule endfaces into contact because the ferrule and fiber are made of different materials with different thermal expansion coefficients, and no ferrule endface has a perfect shape. The axial compressive force deforms the ferrule endfaces, and this can realize stable PC connection [8]–[11].

Finally, we sometimes have to consider an external force of tens of newtons interacting with the fiber cables. If such a force interacts with a small optical connector, the plug housing will be deformed by more than 10 µm, which is far greater than the alignment tolerance. To solve this problem, a ferrule 'floating mechanism' has been widely used (d). The ferrule is not fixed to the plug housing but is held in the housing with a secured gap of about 0.1 mm. A deformation of several tens of µm caused by external force is absorbed by this gap and does not affect the ferrule alignment accuracy.

B. Multifiber coupling connectors

Multifiber connectors are also required to meet the four above conditions (a) to (d) by using a different technology. The multifiber ferrule is a precision plastic molded ferrule. In molding technology, although it is difficult to ensure the accuracy of absolute dimensions, it is easy to achieve accuracy in the relative positions of holes by ensuring the accuracy of the mold (a). Two ferrules are aligned by two guide pins instead of the split sleeve of the simplex connector to meet condition (b). The MT connector [12] (IEC 61754-5) is a typical multifiber connector that is already widely used. The multifiber push-on (MPO) connector has also been developed [13] (IEC 61754-7) for use in a termination cabinet, which is a demarcation point between plant for the telecommunication carriers and users in buildings. Today, a huge number of MPO connectors are used to connect transceiver modules in data center systems. The MPO connector employs a push-on pull-off mechanism with an MT ferrule alignment mechanism. The ferrule endface is polished obliquely with an angle 8° to the plane perpendicular to the ferrule axis so that reflected light is not transmitted in the reverse direction. The fiber ends are designed to protrude slightly at the ferrule endface to allow PC connection between multiple fibers. Since there are some variation in the fiber protrusion, if there is a large number of fibers, it may not be possible to guarantee the contact of all the fibers. Even in this case, since the ferrule endface is obliquely polished, the reflection can be eliminated. This feature meets the above condition (c). A ferrule 'floating mechanism' is also used in the MPO connector to meet condition (d).

The single-mode zirconia ferrule and MT ferrule were developed in the late 1980s. Thirty years later, they are still used in most single-fiber and multifiber coupling PC connectors.

3. Requirements and Their Solutions

3.1 Performance and Reliability Improvement (1980s)

3.1.1 Attenuation Improvement

The main cause of attenuation at the connection point is the lateral misalignment of a pair of fiber cores. For single-mode fiber connection, the 1980s dimensional accuracy level of ferrules and optical fibers is insufficient to ensure a low insertion loss. Therefore, a tuning method, whereby the fiber core offset (fiber core to ferrule center) is aligned with the key direction of a connector, has been widely used to reduce the insertion loss of the connector. By orienting the fiber-core offset of each ferrule in the same direction, a smaller relative lateral offset can be achieved between the fiber cores than with random concatenation, thereby reducing the insertion loss as shown in Fig. 4 [14]. This method was standardized for the IEC 61755-3 series [11]. Recently, the dimensional accuracy of ferrules and optical fibers has improved. The use of these highly accurate ferrules makes the tuning process unnecessary. However, the core position distribution of tuned connectors is different from the core position distribution of untuned connectors, so discussions regarding compatibility with existing connectors are ongoing.

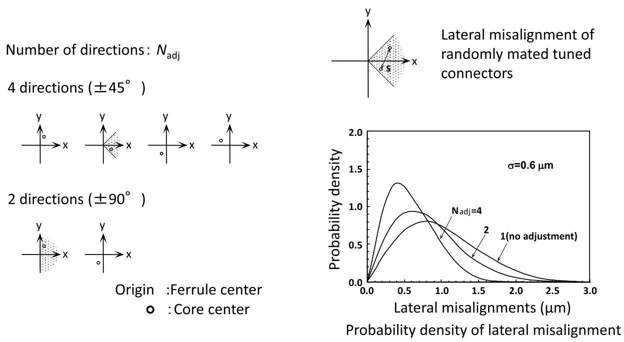

Fig. 4 Tuning technique.

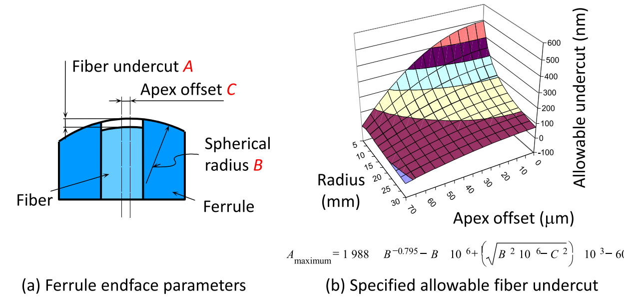

Fig. 5 Ferrule endface geometry.

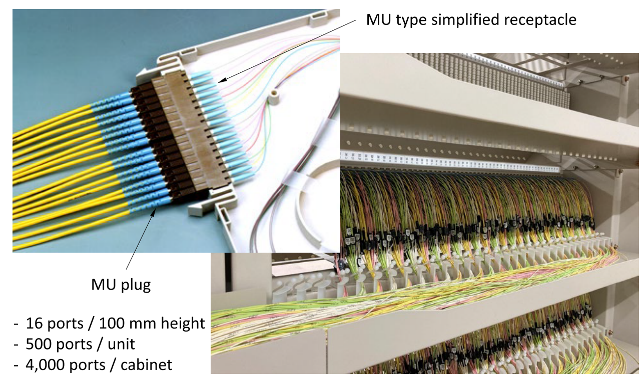

Fig. 6 MU connectors and fiber termination module.

3.1.2 Return Loss Improvement

The first practical PC connectors were produced by polishing the fiber with a diamond polishing agent. This polishing process results in a damaged layer at the fiber endface. In silica fiber, the refractive index of the damaged layer is slightly higher than that of the original fiber core. Therefore, this high refractive index layer generates optical reflection at the connection interface. It was known that the return loss could be improved by removing the damaged layer with a soft abrasive, however, the former polishing agent which has a higher polishing rate for silica causing the problem of fiber undercut. A reliable connector subjected to a low reflection PC polishing technique (sometimes called a UPC connector) was realized using additional fine grain S_iO_2 polishing after the diamond polishing process. This method achieved a ferrule endface with almost no fiber undercut because the polishing rates for zirconia and silica fiber are almost identical [7]. This polishing method is still widely used.

3.1.3 Reliability Improvement

As mentioned above, PC connection would be maintained by ferrule endface deformation with axial compressive force even if there is some fiber withdrawal. The smaller curvature radius, the greater deformation of the ferrule endface which can compensate for greater fiber withdrawal. However, the endface stress and the permanent fiber withdrawal tend to increase as the radius of curvature decreases. NTT optimized the ferrule end geometry in the early 1990s to ensure long-term reliability as shown in Fig. 5(a) [9], [10]. The optimized values are a spherical radius of 10–25 mm, an initial fiber undercut of less than 50 nm, and an apex offset of less than 50 μm. These parameters are related to each other; therefore, the allowable fiber undercut is specified by a function instead of the above fixed values for the IEC 61755-3 series as shown in Fig. 5(b) [11].

3.2 Miniaturization and Cost Reduction (1990s)

In the late 1980s, a large number of optical connections that took up little space were required for transmission, switching and subscriber systems. A compact and multiple optical backplane connector was needed to realize advanced optical system equipment with a high packaging density. Compact connectors were also needed to realize a large number of optical fiber cable terminations inside telephone offices. In the early 1990s, the size of zirconia ferrules was minimized while maintaining the performance and reliability of SC connectors, and a 1.25 mm O.D. zirconia ferrule and MU connector were developed [15]–[17].

In the 1990s, FTTH development became active, and a very low-cost optical connector was required. The simplified receptacle structure is one low-cost solution [18]. Figure 6 shows the MU-type simplified receptacle. It achieved low-cost and high-density fiber cable termination (4,000 ports/cabinet) for the FTTH system [2]. NTT uses this system for over 25 million FTTH subscribers.

In the late 1990s, an optical transceiver module standard called the small form factor (SFF) emerged, and the LC connector was developed. The LC connector employs a 1.25 mm O.D. zirconia ferrule as used with the MU connector, but it differs from the MU connector in that the latch is on the plug side that connects to the adaptor or the receptacle. Therefore, metal materials can be used for the receptacle attached to the transceiver module. This is advantageous for EMC. The LC connector is widely used in both telecommunication systems and LAN or data center systems.

3.3 High Power Issues (2000s)

In the 2000s, Raman-amplifier-based optical network systems were installed in commercial networks, and there is a possibility that high-power optical signals will be transmitted through existing optical cables and optical connectors. The relationship between insertion loss and temperature increase at the connection point has been studied. We can use standard PC connectors on condition that they have a low insertion loss of not more than 0.25 dB and completely clean endfaces [19].

Plug style optical attenuators are also widely used for adjusting the transmission loss in high-power transmission systems. Temperature increases and their influence on connection stability have been studied, and long-term reliability has been confirmed for an incidence power of 300 mW at 70°C, 85% R.H., and 2,000 hrs for SC-plug style attenuators with 10 dB attenuation [20], [21].

3.4 Beyond the Capacity Crunch (2010s)

3.4.1 Multicore Fiber Connector

Optical communication traffic continues to increase; however, the transmission capacity of conventional single-mode fiber has now reached around 100 Tb/s, which is assumed to be the maximum value [22]. Multi-core fiber (MCF) is one of the most promising candidates for achieving ultra-wideband optical transmission in the near future [23].

For MCF connectors, the above mentioned four required conditions (a) to (d) are the same as for standard SMF connectors. In addition to these four conditions in SMF, an additional condition is needed namely (e) to precisely match the angle around the ferrule axis. The MCF connector can also use a zirconia ferrule (a) and the split sleeve (b). A physical contact technology (c) can be used in the same way, but the required ferrule end face geometry is slightly different because there are some cores that are not located at the center [24].

Conditions (d) and (e) are conflicting conditions because the ferrule floating mechanism causes ferrule rotation. For example, an MU connector has a 0.1 mm gap in each direction between the ferrule flange and the plug housing. This gap allows a ferrule rotation of ±10°, however this value does not satisfy the typical allowable MCF tolerance of ±0.5°. To realize an angle tolerance of ±0.5°, an MU-type MCF connector that incorporates Oldham's coupling mechanism was proposed in the early 2010s [25]. Figure 7 shows the structure of a ferrule with an Oldham's coupling mechanism.

The use of MCF is also being considered for large scale data centers that require extremely high-density optical wiring.

On the other hand, an MCF patch cord has polarity because each core ID should be connected to the same core ID. To connect to a receptacle such as an optical transceiver module, it is necessary to have Oldham's coupling mechanism inside one plug alone, but if it is limited to the connection of cables, it would be enough to have Oldham's coupling mechanism in a connection point consisting of a pair of plugs [26].

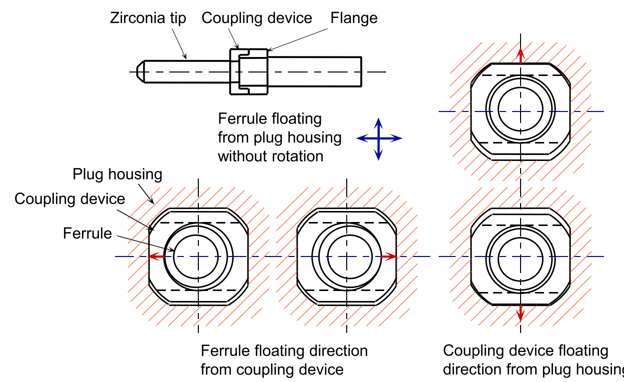

Fig. 7 MCF connector with Oldham's coupling mechanism.

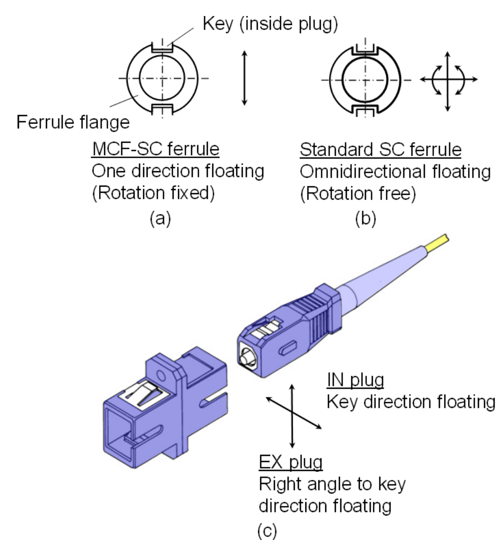

Fig. 8 Structure of SC type MCF connector.

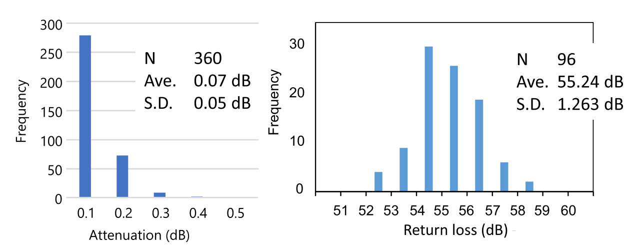

Fig. 9 Characteristics of MCF connectors attached to standard O.D. 4-core MCF.

Figure 8 shows an SC type MCF connector, and Fig. 9 shows the typical attenuation and return loss of an MCF connector attached to a standard 4-core MCF.

In addition, an LC type MCF connector has been proposed that does not use Oldham's coupling and that has a structure in which the angle of the ferrule is fixed in the plug alone and that floats when connected [27].

3.4.2 Hollow-Core Fiber Connector

Studies on hollow-core fiber (HCF) have progressed [28]–

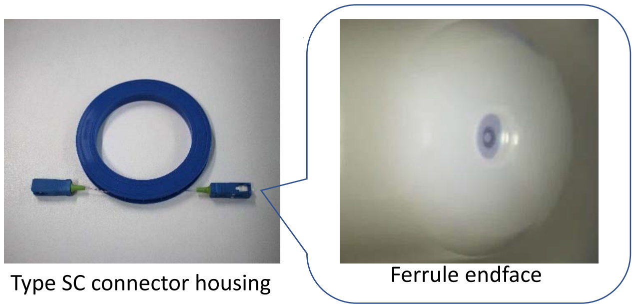

Fig. 10 HCF connector using a thin glass plate attached obliquely to a ferrule endface.

[34], and recently a Nested Antiresonant Nodeless Fiber (NANF) with a propagation loss of 0.174 dB/km has been reported [34]. This value indicates that NANF has the potential to be used in optical communication networks. HCF can expand the mode field diameter propagated in a single mode without any non-linearity effect or fiber fuse phenomenon. HCF is also attracting attention for its low-latency characteristic compared with silica fiber and its low dispersion, making it suitable for quantum communication.

The PC connector cannot be adopted for the HCF, which has a fragile hollow microstructure. On the other hand, at the connection point there is no Fresnel reflection at the fiber end because the refractive index of HCF core is the same as air, and HCF has large tolerance of gap between fibers because it has very small numerical aperture, no PC connector is required. Figure 10 shows the HCF connector using a thin glass plate attached obliquely to a ferrule endface [35], [36]. A typical HCF connector attenuation of 0.5 dB and a return loss of 50 dB are reported.

4. Conclusions

Fiber-optic connectors, which are indispensable to the construction of optical communication networks, have improved with the progress made on communication systems. However, the basic structure of the optical connector has not changed since it was first put to practical use. Single-fiber coupling connectors have used zirconia ferrules and multifiber coupling connectors have used MT ferrules for more than 35 years, and there is no prospect of any radical change. This is one reason for the structure of the single-mode fiber remaining unchanged. However, new optical fibers, namely multicore fiber and hollow-core fiber that cannot be handled in the same way as single-mode fiber, have appeared in the last 10 years. Optical fiber connector technologies will continue to evolve.

Acknowledgments

This work was partly supported by the National Institute of Information and Communications Technology's (NICT) research and development of spatial mode control optical transmission infrastructure technology for the Beyond 5G era.

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