Drawing from the past 40 years of optical fiber communications systems being put into practical use, this paper detail
The MPO connector employs a push-on pull-off mechanism (IEC 61754-5) is a typical multifiber connector that is 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)

(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.
(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 SiO₂ 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) 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)

(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-wide-band 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.

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].

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...
Ferrule endface technologies will continue to evolve. As of the last 10 years, optical fiber connector systems 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.

in which the angle of the ferrule is fixed in the plug alone and that floats when connected [27].

(2) Hollow-core fiber connector

Studies on hollow-core fiber (HCF) have progressed [28-34], 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.

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