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Return Loss Measurement Procedure for Multicore Fiber Connectors

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SUMMARY Multi-core fiber (MCF) is one of the most promising candidates for achieving ultra-wideband optical transmission in the near future. To build a network using MCF, a high-performance and reliable MCF connector is indispensable. We have developed an SC-type optical connector for MCF and confirmed its excellent optical performance, mechanical durability, and environmental reliability. To put the communication system using MCF into practical use, it is necessary to establish a procedure for measuring the initial connection characteristics. Fan-in / fan-out (FIFO) devices are indispensable for measuring the connection characteristics of MCF connectors. To measure the return loss of the MCF connector, it is necessary to remove the influence of reflection at the FIFO itself and at the connection points with the FIFO. In this paper, we compare four types of return loss measurement procedures (three usual method and a new method we proposed) and find that most stable measurement method involves using our new method, the OCWR method without FIFO. The OCWR method without FIFO is considered to be the most advantageous when used for outgoing inspection of connectors. The reason is that it eliminates the measurement uncertainty caused by the FIFO and enables speedy measurement.

key words: *multicore fiber, optical connector, return loss, fan-in / fan-out*

1. Introduction

Communication technologies using single-mode optical fibers (SMFs) have become widespread worldwide. However, with the spread of video distribution services using the Internet and smartphones, the communication traffic through optical networks continues to increase year by year, and there is concern that the transmission capacity of the SMF currently in use will reach its limit [1]. Therefore, a transmission system that uses multicore fiber (MCF) with multiple cores in one fiber is being studied as a candidate for achieving a large increase in communication capacity [2]–[5].

In recent research, a 4-core MCF with a cladding diameter of 125 μm was investigated for early commercialization [6]. A transmission experiment using this MCF achieved a long-distance transmission of 3001 km with a capacity of 319 Tbit/s [7].

On the other hand, to build a communication network using optical fibers, it is necessary to have optical connectors designed to link cables and modules and that ensure compatibility when interconnected by multiple vendors. Optical connectors for MCFs are also indispensable in transmission systems using MCF. Several types of optical connectors for MCF have been developed so far, and it has been confirmed that they have practicality that can be used in optical networks [8]–[23].

For the optical connectors that are indispensable for transmission systems, the return loss at the connection point must be measured at the time of shipping to confirm that they meet the standard specifications. When measuring the return loss of MCF, it is essential to connect the cores of each MCF and SMF using fan-in / fan-out (FIFO) devices [24]–[28]. The effect of a FIFO device on measurements must be considered [29].

As the return loss measurement procedures at one connection point, the Optical Time-Domain Reflectometer (OTDR) method, the Optical Frequency-Domain Reflectometer (OFDR) method, and the Optical Low-Coherence Reflectometer (OLCR) method, which have spatial resolution, and the Optical Continuous Wave Reflectometer (OCWR) method, which is usually used for shipping inspection are specified in IEC 61300-3-6.

We tried four procedures [21], [22], [29]; (1) the OCWR method, (2) the OTDR method, and (3) the OLCR method which used FIFO devices, and (4) the OCWR method without FIFO. Method (4) is the new method which we proposed with the conventional OCWR method using a single-mode single-core fiber (SMF) probe directly connected to the MCF without FIFO. This measurement method differs from other methods in that it does not use a FIFO which would be magnify the measurement uncertainty. In this paper, we compared four types of MCF connector return loss measurement procedures, and clarified the advantage of our proposed OCWR measurement method without FIFO because it can measure all cores in one time, it has low uncertainty and it can measure any fiber length.

2. Return Loss Measurement Procedures for MCF Connectors

We attached SC-type optical connectors for MCF [21] to both ends of a 4-core MCF with a standard outer diameter [6], [7], and measured the return losses at one connection point using the following measurement procedures 2.1 to 2.4.

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2.1 OCWR Method with FIFO

First, we tried the OCWR method, which is often used for the pre-shipping inspection of optical connectors, because the measurement system is simple and inexpensive, and the measurement time is short.

The OCWR method does not have any spatial resolution, and the total reflection in the measured optical path, including the FIFO device, would be obtained. Figure 1 shows the measurement setup of the OCWR method with FIFO. Since there are multiple connection points in each optical path, we used an ASE light source with a wavelength of 1550 nm to reduce the measurement uncertainty due to the interference from multiple reflections.

For measurement procedure, first, we set a return loss of −14.7 dB as a reference (1) when the connection point (c) between the two patch cords with MCF connectors in Fig. 1 is opened, and then the MCF connectors were connected to each other and terminated with an index matching block for measurement (2).

Figure 2 shows the results of a total of 32 return loss measurements at the 16 connection points of the 4-core MCF connectors, and Table 1 shows the average return loss of each core.

As shown in Fig. 2, the average measurement result was 45.80 dB, which was lower than that of a standard optical connector for SMF. We consider that this is because the reflection in the FIFO and at the connection points with the FIFO affect the measurement result of the return loss at an MCF connection point. On the other hand, the return loss of the PC optical connector is caused by the damaged layer generated during end face polishing, but it is unlikely that the refractive index of the damaged layer changes significantly between the cores. The return losses of each core shown in Table 1 have similar values, which supports this point.

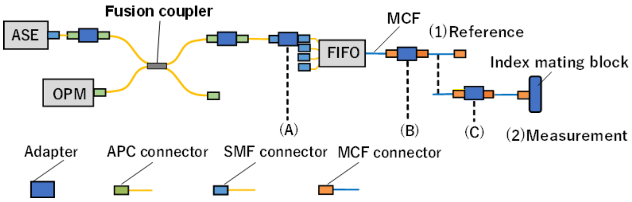

Fig. 1 OCWR measurement setup with FIFO.

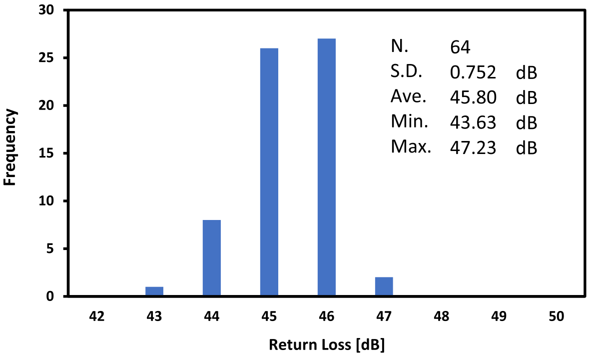

Fig. 2 OCWR measurement results with FIFO.

Table 1 Average return loss of each core measured by OCWR with FIFO

Core ID	Return loss (dB)
Core 1	46.39
Core 2	45.93
Core 3	45.64
Core 4	45.27

We considered the way in which the attenuation and return loss at connection points A and B in Fig. 1 affect the measured values. Figure 3 shows the level diagram in the measurement setup when we used the input power P_0, reference optical power P_{Ref}, and measured power P_{m} shown in Fig. 1. Equations (1) and (2) show the calculated return loss at the connection point B and C of the MCF connector based on the level diagram shown in Fig. 3.

$$RL_{\mathrm{B}} = -10\left(\frac{P_{\mathrm{m}}R_{\mathrm{air}}}{P_{\mathrm{Ref}}} - \frac{RL_{\mathrm{A}}}{IL_{\mathrm{A}}{}^2}\right) \tag{1}$$

$$RL_{\mathrm{C}} = -10\log\left(\frac{P_{\mathrm{m}}R_{\mathrm{air}}}{P_{\mathrm{Ref}}} - \frac{IL_{\mathrm{A}}{}^2RL_{\mathrm{B}} + RL_{\mathrm{A}}}{IL_{\mathrm{A}}{}^2IL_{\mathrm{B}}{}^2}\right) \tag{2}$$

Where R_{air}: the reflectance of the fiber end face and air, $IL_{\mathrm{A}}{}^2$: attenuation at point A (round trip), $IL_{\mathrm{B}}{}^2$: attenuation at point B (round trip), RL_{A}: return loss at point A, RL_{B}: Return loss at point B calculated by equation, RL_{C}: Return loss at point C calculated by equation, and P_{m}: measured optical power.

The return loss at each connection point of the optical path is considered to be about −50 dB, and the effect on the −14.7 dB calibrated at point (C) is small. In other words, the 50 dB optical power at each connection point are small compared to the 14.7 dB at point (C) as shown in Fig. 3, which means that the loss is buried in the reference power. In contrast, the measured optical power is about −50 dB, so the return loss at the other connection points cannot be ignored. Thus, the blue line in Fig. 3 shows the ideal measured optical power of P_{m}, while the red line in Fig. 3 shows a higher optical power because the return loss at each connection point is included.

Table 2 shows an example of the measured attenuation and return loss at each connection point. Where RL_{B1} and RL_{C1} are the return loss at connection points A and B in Fig. 3, respectively. Figure 4 shows the results of the calcu-

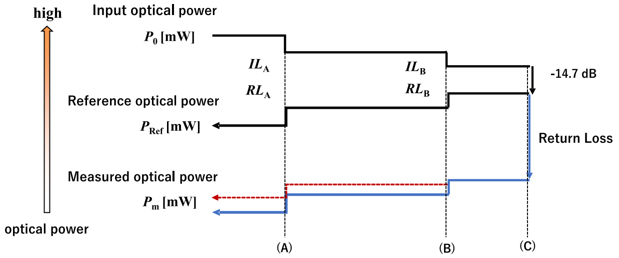

Fig. 3 Level diagram of OCWR measurement setup.

Table 2 An example of attenuation and return loss at each connection point

(a) Attenuation

Core ID	IL_A (dB)	IL_B (dB)
Core 1	0.48	0.4
Core 2	0.58	0.23
Core 3	1.51	0.12
Core 4	1.44	0.16

(b) Return loss

Core ID	RL_A (dB)	RL_{B1} (dB)	RL_B (dB)	RL_{C1} (dB)	RL_C (dB)
Core 1	50.41	48.03	53.58	46.72	56.27
Core 2	50.66	47.51	51.86	46.48	55.58
Core 3	50.86	46.68	52.98	46.08	57.07
Core 4	50.36	46.21	52.17	45.14	53.14

(c) Reference optical power and measured power

Core ID	P_{Ref} (dBm)	P_m (dBm)
Core 1	-15.95	-49.28
Core 2	-16.09	-48.90
Core 3	-18.02	-50.00
Core 4	-17.84	-49.35

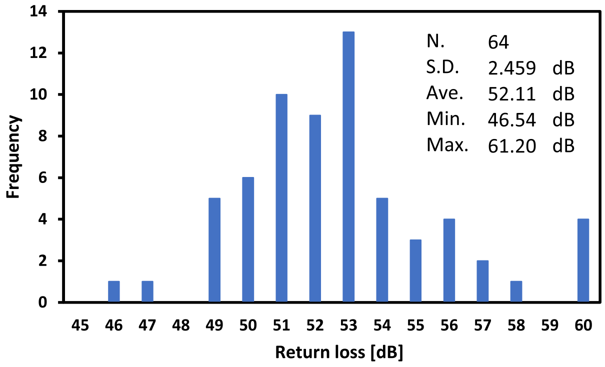

Fig. 4 Calculated return loss with OCWR measurement results with FIFO.

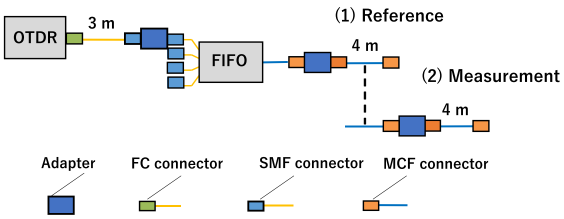

Fig. 5 OTDR measurement setup with FIFO.

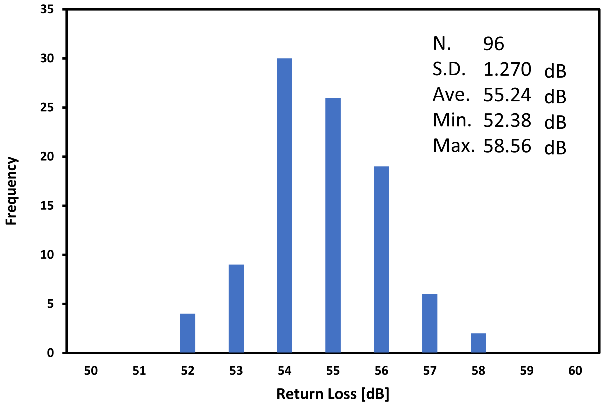

Fig. 6 OTDR measurement results with FIFO.

Table 3 Average return loss of each core measured by OTDR with FIFO

Core ID	Return loss (dB)
Core 1	55.43
Core 2	54.58
Core 3	55.11
Core 4	55.83

lation by applying the previously measured attenuation and return loss at each connection point using Eq. (2).

By substituting the values obtained at each connection point in Eq. (2), the return loss of connection point C can be calculated. Here, the units of the values obtained at each connection point need to be converted to mW.

The calculated results confirmed an average of 52.11 dB, indicating that a return loss of more than 50 dB can be expected. In addition, the distribution of the calculation results was approximately normal distribution. However, the standard deviation was larger than the original measurement value. This is considered to be due to the increased uncertainty in the measurement because of a slight difference in the return losses at the connection points A and B have a large effect on the calculated result in Eq. (2)

2.2 OTDR Method with FIFO

The OTDR method launches a signal pulse from one end of an optical fiber and detects backscattered light. It is mainly suitable for long-distance measurement and is used for the maintenance and inspection of optical networks. We used high resolution OTDR (OP940 manufactured by Opto Test), which has a minimum spatial resolution of 3 m. Figure 5 shows the measurement setup of the OTDR method with FIFO.

Since the spatial resolution of this OTDR is 3 m, 4 m-long MCF patch cords were assembled to measure the return loss at one connection point, and a total of 96 return losses were measured at the 24 connection points of the 4-core MCF connector. Figure 6 shows the distribution of the measured return losses and Table 3 shows the average return loss of each core.

Figure 6 indicates a normal distribution, and the average return loss was 55.24 dB. This value is 2 to 3 dB higher than the average return loss of a normal SMF optical connector measured by the OCWR method, but it is a reasonable value because the OTDR method does not include the reflection at the termination. In addition, as shown in Table 3, the return loss of each core had a similar value. Based on these points, we consider that the return loss measured with the OTDR method to be close to the true return loss of the MCF connector. However, the OTDR method has a problem in that an accurate measurement cannot be performed unless the cable between the connectors is long, so it is unsuitable for the pre-shipping inspection of optical connectors.

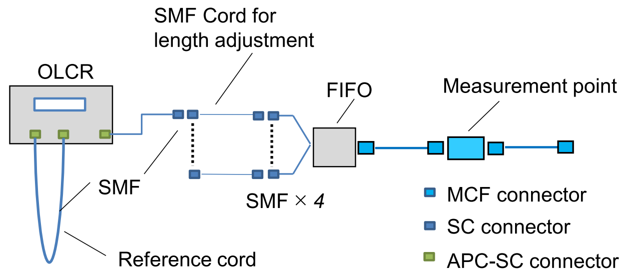

Fig. 7 OLCR measurement setup with FIFO.

Table 4 Average return loss of each core measured by OLCR with FIFO

Core ID	Return loss (dB)
Core 1	51.2
Core 2	53.0
Core 3	49.7
Core 4	46.5

2.3 OLCR Method with FIFO

Since the OLCR method has an extremely high spatial resolution, we can expect to obtain an accurate return loss measurement at one connection point. We use an ‘OCCR’ manufactured by Optogate as the measuring instrument. The measurement setup is shown in Fig. 7. To measure the return loss at the MCF connection point with the OLCR method, we require a reference cord that matches the optical path length including the FIFO for each core. Therefore, we prepared a reference cord with an optical path length equal to the total optical path length after connecting the SMF cord for length adjustment so that each port of the FIFO has the same optical path length. At this time, since the loss of the entire FIFO becomes large, the return loss when the measurement point is released is calibrated to −14.7 dB.

With the OLCR method, the value fluctuated greatly with each measurement. This is thought to be due to the polarization fluctuation in the long optical path length including the FIFO and there was some polarization-dependent loss (PDL) with the FIFO we used. Therefore, Table 4 shows the average value obtained for 100 measurements of each port.

Compared with the core-to-core variation (Table 1) obtained with the OCWR method and the OTDR method (Table 3), the maximum variation was less than 1 dB, and a large variation of 6.5 dB was observed with the OLCR method as shown in Table 4. We considered that the cause of this large variation was the loss of the entire measurement system, and we compared the attenuation of the optical path including the FIFO measured with the OLCR method with the attenuation measured separately using a light source and a power meter. The results are shown in Table 5.

From Table 5, the results obtained from the attenuation results measured with the OLCR method did not match the attenuation measured with a light source and power meter. The above results suggest that the OLCR method is unsuitable for measuring the return loss at one connection point of the MCF connector via FIFO.

Table 5 Optical path attenuation measured with OLCR compared with that measured with a light source and power meter

Core ID	OLCR (dB)	Light source and power meter (dB)
Core 1	3.41	1.73
Core 2	1.96	1.82
Core 3	2.50	3.65
Core 4	3.90	2.73

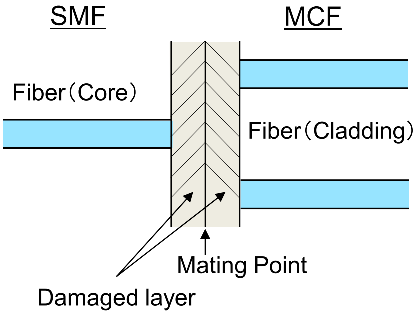

Fig. 8 Image of SMF to MCF connection point.

For the OLCR method, shortening the optical path length including the FIFO is expected to reduce the measurement uncertainty due to polarization and other factors.

2.4 OCWR Method without FIFO

A FIFO device is indispensable when measuring the return loss of an MCF connector. As a result of examining measurement methods (1) to (3), we found that it is difficult to eliminate the influence of the attenuation, return loss and polarization-dependent loss of the FIFO. Therefore, we investigated the case where we connected the MCF connector directly to a conventional SMF OCWR measuring instrument without using a FIFO.

The dominant factor in the return loss at the PC optical connector connection is the damaged layer caused by end face polishing [30]. Assuming that the processed damaged layer formed on the end face is uniform for an optical fiber with an outer diameter of $125\,\mu$m, we can predict that the return loss of the region where the core and the core are in contact by measuring the return loss of the region where the core and the cladding are in contact.

Since the 4-core MCF that we used does not have a core in the center, the image of the connection region is as shown in Fig. 8.

To calculate the reflection by the damaged layer, a model in which the light emitted from the core passes through the damaged layer and enters the cladding is shown in Fig. 9, and the light emitted from the core passes through the damaged layer and enters the core as shown in Fig. 10. Where n_1: refractive index of the fiber core, n_2: refractive index of the fiber cladding, n_{dL1}: refractive index of the damaged layer formed in the fiber core, n_{dL2}: refractive index of the damaged layer formed in the fiber cladding, d_{dL1}: the thickness of the damaged layer formed in the fiber core,

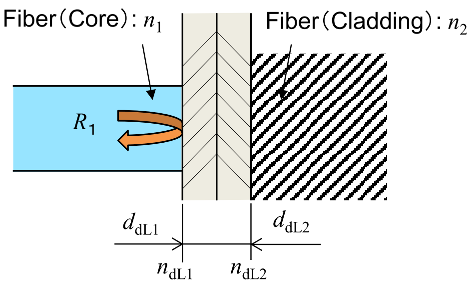

Fig. 9 Reflection model of core to cladding contact region.

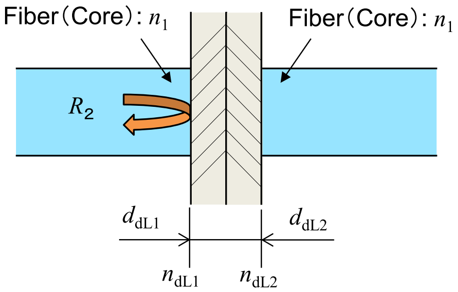

Fig. 10 Reflection model of core to core contact region.

d_{dL2}: the thickness of the damaged layer formed in the fiber cladding.

To calculate the return loss we used the following equation with reference to the method employed in the calculation of the first PC optical connector that was low-reflection polished using ultrafine S_iO_2 particles and reported by Kanayama et al. in 1992 [30].

$$P_{\mathrm{R}} = \frac{\left\{(n_1 - n_2)B + \left(n_2\frac{n_{\mathrm{dL1}}}{n_{\mathrm{dL2}}} - n_1\frac{n_{\mathrm{dL2}}}{n_{\mathrm{dL1}}}\right)A\right\}^2 + \left\{\left(\frac{n_1 n_2}{n_{\mathrm{dL2}}} - n_{\mathrm{dL2}}\right)C + \left(\frac{n_1 n_2}{n_{\mathrm{dL1}}} - n_{\mathrm{dL1}}\right)D\right\}^2}{\left\{(n_1 + n_2)B - \left(n_2\frac{n_{\mathrm{dL1}}}{n_{\mathrm{dL2}}} + n_1\frac{n_{\mathrm{dL2}}}{n_{\mathrm{dL1}}}\right)A\right\}^2 + \left\{\left(\frac{n_1 n_2}{n_{\mathrm{dL2}}} + n_{\mathrm{dL2}}\right)C + \left(\frac{n_1 n_2}{n_{\mathrm{dL1}}} + n_{\mathrm{dL1}}\right)D\right\}^2} \quad (3)$$

n_1 : Fiber (Core)
n_2 : Fiber (Cladding)
n_{dL1} : Damaged layer (Core)
n_{dL2} : Damaged layer (Cladding)

$$\begin{aligned} A &= \sin\delta_1 \sin\delta_2 \\ B &= \cos\delta_1 \cos\delta_2 \\ C &= \cos\delta_1 \sin\delta_2 \\ D &= \sin\delta_1 \cos\delta_2 \\ \delta_1 &= 2\pi n_{\mathrm{dL1}} d_{\mathrm{dL1}}/\lambda \\ \delta_2 &= 2\pi n_{\mathrm{dL2}} d_{\mathrm{dL2}}/\lambda \end{aligned}$$

$$RL = -10\log_{10}(P_{\mathrm{R}})\,[\mathrm{dB}] \quad (4)$$

The optical connector for MCF this time has also undergone low reflection polishing with ultrafine S_iO_2 particles, which are now usually used, but the conditions have been optimized compared with those used in 1992, and the actual return loss has improved. Therefore, we calculated the refractive index increase coefficient δ of the damaged layer back from the measured value of the return loss obtained with the OTDR method while retaining the damaged layer thickness obtained in 1992 [30]. In addition, the thickness of the processed damaged layer is a value taken from the previous study by co-author Nagase. First, he prepared multiple standard refractive index liquids and measure the return loss when applied to the PC polished end face. Next, the relationship between the refractive index of the applied liquid and the return loss was calculated when the refractive index and thickness of the damaged layer. And the refractive index and thickness of damaged layer was obtained by the least square method to best fit to measured values [30].

Table 6 The thickness and refractive index of the damaged layer.

(a) Thickness of the damaged layer

Damaged layer	Thickness (μm)
d_{dL1}	0.07
d_{dL2}	0.07

(b) Refractive indexes of the fiber and the damaged layer

	Symbols	Refractive index
Fiber	n_1	1.450
	n_2	1.444
Damaged layer	n_{dL1}	1.453
	n_{dL2}	1.447

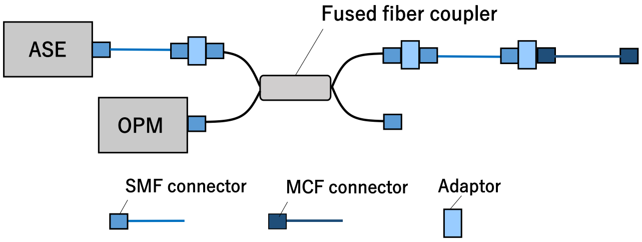

Fig. 11 OCWR measurement setup without FIFO.

Assuming that the refractive index of the damaged layer in the core region and the refractive index of the damaged layer in the cladding region increase with the same coefficient δ, Eqs. (5), (6) and (7) show that for both damaged layers. The refractive indexes n_{dL1} and n_{dL2} were obtained. Table 6 shows the obtained thickness and refractive index of the damaged layer. The refractive indexes n_1 and n_2 are the refractive indexes of the MCF we used.

$$n_{\mathrm{dL1}} = \delta n_1 \quad (5)$$

$$n_{\mathrm{dL2}} = \delta n_2 \quad (6)$$

$$\delta = 1.0022 \quad (7)$$

Next, we measured the return loss of the optical connector for MCF when the SMF core and MCF cladding were connected without using a FIFO. The OCWR method was used for the measurement. The measurement setup is shown in Fig. 11, and the measurement results are shown in Fig. 12. As shown in Fig. 8, the core and cladding of the fiber are connected, and the light propagates from the SMF core to the MCF cladding. Light propagating through the cladding and reflected at the end hardly couples to the SMF core. Therefore, we do not need termination as index matching block while measuring return loss.

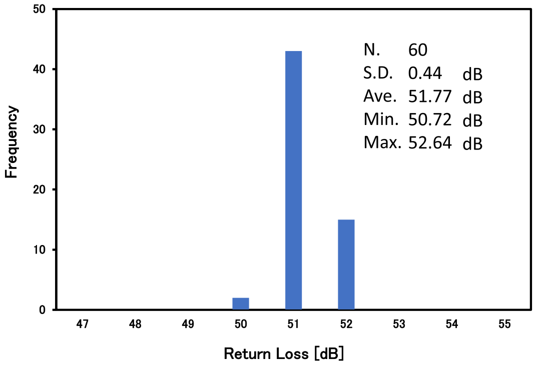

Fig. 12 OCWR measurement results without FIFO.

Table 7 Comparison of calculated and measured results

Connecting point	Calculated RL (dB)	Measured RL (dB)
Core - Cladding	51.61	51.77
Core - Core	55.86	55.24

Table 7 shows the results compared the return loss obtained by Eqs. (3) and (4) with the measured values shown in Fig. 12. The return loss at the connection between the core and the cladding was about 3 dB lower than the average return loss at the connection point between the cores measured by OTDR, but this is the difference between the refractive indexes of the core and the cladding. It was almost the same as the calculated result. In addition, this method has less measurement uncertainty than method (1) using Eq. (2), enables stable measurement, and does not return the reflection on the opposite side of the connection point. This is an easy measurement method without the need for termination treatment.

From the above, we confirmed that we can estimate the return loss between each core by directly measuring the MCF optical connector with the return loss measurement setup for SMF by the OCWR method without using a FIFO device. Since it is the OCWR method, it is considered to be the most suitable approach for pre-shipment product inspection.

3. Discussions

We tried four procedures; (1) the OCWR method, (2) the OTDR method, and (3) the OLCR method which used FIFO devices, and (4) the OCWR method without FIFO. Method (4) is the new method which we proposed with the conventional OCWR method using a single-mode single-core fiber (SMF) probe directly connected to the MCF without FIFO. This measurement method differs from other methods in that it does not use a FIFO, which would be magnify the measurement uncertainty. Normally, a FIFO is required when measuring the return loss of an optical connector for MCF. However, after examining measurement methods (1) and (3), we found that it is difficult to eliminate the influence of the attenuation, return loss and polarization-dependent loss of the FIFO. Method (2), OTDR, can eliminate the influence of FIFO, however, it requires long fiber length between connectors around 4 m or more.

Table 8 Comparison of four MCF connector return loss measurement methods

Method	Accuracy	Uncertainty	Fiber length	Measurement time
OCWR w FIFO	○	△	Any	○
OTDR w FIFO	◎	○	> 4 m	△
OLCR w FIFO	△	×	Any	△
OCWR w/o FIFO	○	◎	Any	◎

The return loss is always measured at the time of shipment inspection at optical connector manufacturing vendors, but in that case, it is required to be able to measure in a short time, to have a small uncertainty, and to conform to any fiber length. Method (4), OCWR without FIFO, is said to be a measurement method that satisfies all these conditions because it can measure all cores in one time, it has low uncertainty and it can measure any fiber length. Table 8 shows the comparison of four MCF connector return loss measurement methods.

4. Conclusions

In this paper, we investigated methods for measuring the return loss of MCF connectors: (1) the OCWR method using FIFO, (2) the OTDR method, (3) the OLCR method, and our new proposal, (4) the OCWR method without FIFO.

With method (1), the return loss at the MCF connection point can be measured correctly, but the measurement uncertainty increases. Method (2) can provide highly reliable measurements but cannot be used for short (3 m or less) patch cords. With method (3), the measurement uncertainty becomes very large due to the polarization fluctuation in the long optical path including the FIFO. With method (4), the contact point between the SMF core and the MCF cladding was measured using a single-core single-mode fiber (SMF) in a normal OCWR measurement setup. If the refractive index of the core and cladding is known, it can be converted from the return loss of the contact between the core and cladding, and the result is close to the method (2) result obtained by measuring a 4-m-long patch cord by OTDR.

From the above, it is considered that the OCWR method without FIFO in (4) has the greatest advantage when used in the shipment inspection of connectors. The reason is that it removes the uncertainty of measurement by FIFO and enables speedy measurement.

Acknowledgments

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