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Optical Performance Analysis
of Single-Mode Fiber Connections

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1. Introduction

Many single-mode optical fiber (SMF) connection techniques, such as fusion splicing, mechanical splicing, and use of optical connectors, are currently used in fiber-to-the-home (FTTH) systems (Keck et al., 1989; Shinohara, 2005). A fusion splice is fabricated by a fusion splice machine (splicer), which is a precision machine containing fiber alignment, video monitor, and arc discharge functions; it has the highest and stablest performance of all the connections. A mechanical splice is a simple and cost-effective connection that requires no electricity. An optical connector is capable of frequent reconnections. Many kinds of connectors have been developed and used in optical networks. Each connection technique determines how or where it should be used. Fiber connections, except fusion splices, are classified into two types of connection states. One is a connection with physical contact (PC), and the other uses refractive-index matching material. PC-type connectors are mostly used for intra-office fiber connections and on premises where frequent reconnections are required. In contrast, connectors and mechanical splices with refractive-index matching material are mostly used in outside facilities, where frequent reconnections are unnecessary but low cost connections are needed. Field-installable connectors using both PC connectors and refractive-index matching material have recently been developed and used in FTTH systems (Nakajima et al., 2007; Hogari et al., 2010).

The optical performances of these fiber connections have been analyzed and reported (Marcuse, 1976; Young, 1991; Kihara et al., 1996), but some points remain unclear. Unexpected faults occurring during and after installation of these fiber connections might detrimentally affect performance. For instance, when an air gap occurs unexpectedly at the contact point with PC-type connectors or connectors using index matching material, the return loss becomes noticeably worse. In addition, contamination and scratches on an optical connector end surface may cause significant performance deterioration of the mated connectors (Albeanu et al., 2003). Understanding the worst possible optical performance of these fiber connections would make it possible to guarantee the overall performance of a system.

In this chapter, the optical performance of SMF connections is reported, various cases of which have been experimentally investigated: connections with (1) air-filled gaps, (2) a mixture of refractive-index matching material and air-filled gaps, and (3) unexpected use of

an incorrectly cleaved fiber end. The cases were assumed to occur accidentally as the result of unexpected failure during and after installation of fiber connections using PC or refractive-index matching material in the field. The various connection cases, classified in their normal and abnormal states, are shown in Fig. 1. In the normal state, the polished fiber ends of a PC connection touch, with no air-filled gap between the ends. A connection using refractive-index matching material has a very small gap between the polished or correctly cleaved fiber ends, and the gap is filled with that material. This chapter details the abnormal connection states of the three connection cases. In section 2, the conventional optical performance analyses of SMF connections based on the D. Marcuse analysis for insertion loss and the W. C. Young et al. analyses for return loss are explained. In section 3, the performance of fiber connections with air-filled gaps is revealed. This case might occur when a fiber connection using PC experiences an unexpected failure, resulting in imperfect PC. In section 4, a loss analysis is reported for fiber connections with a mixture of refractive-index matching material and air-filled gaps. This case might occur when an optical connector or a mechanical splice using refractive-index matching material experiences an unexpected failure. The performance deterioration of fiber connections using an incorrectly cleaved fiber end is demonstrated in section 5. This case might occur when a field-assembly connector or a mechanical splice experiences an unexpected failure. Finally, this chapter is summarized in section 6.
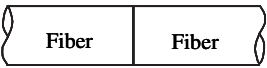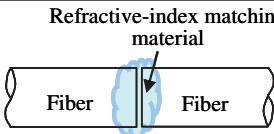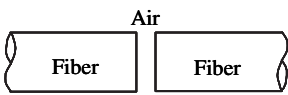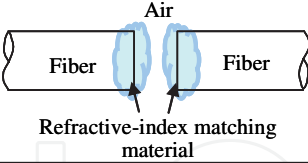

Fig. 1. Various states of fiber connections.

2. Overview of conventional analyses of SMF connections

This section explains the conventional optical performance analyses of SMF connections. The two important parameters for the optical performance of fiber connections are insertion loss and return loss. The insertion loss in dB is derived by multiplying -10 by the log of the transmission coefficient T, i.e., -10 log(T). Here, T denotes the ratio of transmitted light power to incident light power at the fiber connection. Similarly, the return loss in dB is derived by multiplying -10 by the log of the reflection coefficient R, i.e., -10 log(R). Here, R denotes the ratio of returned light power to incident light power at the fiber connection. In this section, the conventional insertion loss analysis of SMF connections based on that by D. Marcuse is first explained. Then, the W. C. Young et al. analyses for return loss are reported.

2.1 Insertion loss

The insertion loss of SMF connections has been analyzed by D. Marcuse (Marcuse, 1976). According to the analysis, when the fundamental mode of SMF is assumed to be approximately expressed by the Gaussian function, the transmission coefficient T can be calculated for the four major factors shown in Fig. 2. The calculation equations are shown below.
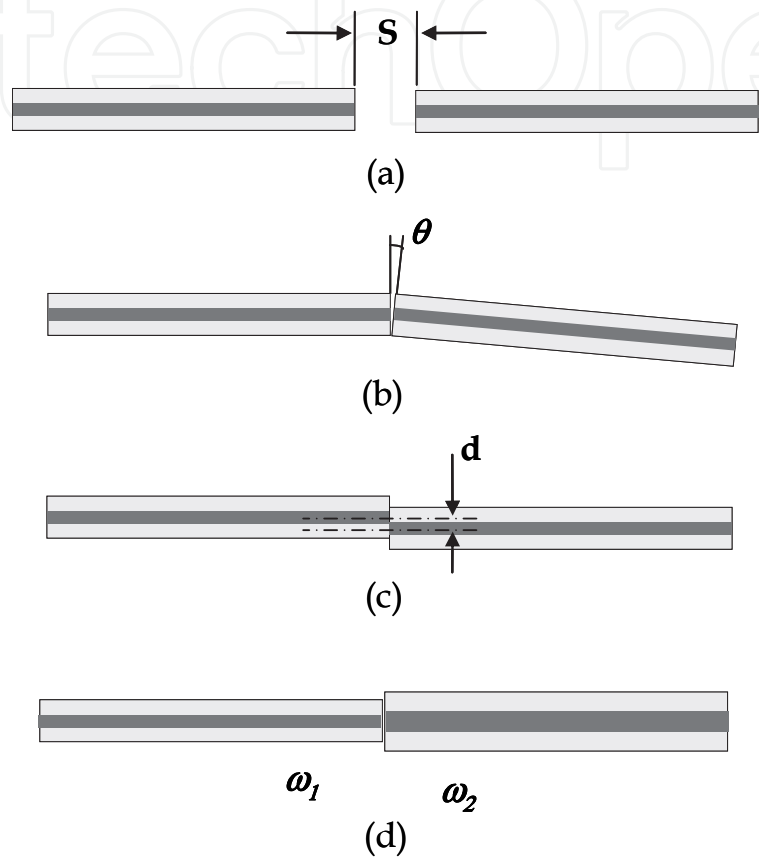

Fig. 2. Four types of insertion loss factors. (a) Gap between fiber ends, (b) misalignment of tilt, (c) misalignment of offset, (d) mode field mismatch.

(a) Gap between fiber ends (when the gap is much larger than the wavelength-order length of the transmitted light)

$$T = \frac{1}{Z^2 + 1} \tag{1a}$$

$$Z = \frac{\lambda S}{2\pi n \omega^2} \tag{1b}$$

(b) Misalignment of tilt

$$T = \exp\left[-\frac{(\pi n \omega \theta)^2}{\lambda^2} \right] \tag{2}$$

(c) Misalignment of fiber offset

$$T = \exp\left[-\frac{d^2}{\omega^2}\right] \tag{3}$$

(d) Mode field mismatch

$$T = \left(\frac{2\omega_1\omega_2}{\omega_1^2 + \omega_2^2}\right)^2 \tag{4}$$

Here, S, θ, d, n, λ, ω, ω_1, and ω_2 are the gap size, tilt, offset, refractive index of the medium between two fibers, wavelength, and the three mode field radii of transmitted light, respectively. These equations are generally and widely used to analyze the insertion loss of an SMF connection.

2.2 Return loss

Return loss is also an important parameter for fiber connections (Young, 1991). A reflection occurs at the boundary between two media with different refractive indices, named a Fresnel reflection (Born & Wolf, 1964). The Fresnel reflection R_0 at the fiber end in a medium is defined by the following equation.

$$R_0 = \left(\frac{n_1 - n}{n_1 + n}\right)^2 \tag{5}$$

Here, n_1 and n denote the refractive indices of the fiber core and the medium, respectively. For instance, when a cleaved fiber end is in air, the refractive indices of the fiber core and air are 1.454 and 1.0, respectively, and the reflection coefficient R_0 is 0.034 (the return loss is 14.7 dB). In this case, the reflected light power is about 3.4 % of the incident power at the fiber end in air, but the value is very large in optical transmission characteristics.

The return loss for a fiber connection without a gap is thought to be negligible. However, we have to consider the return loss for optical fiber connections with a gap between the fiber ends. An analysis of the reflection coefficient caused by a gap between fiber ends is based on multiple reflections behaving like a Fabry-Perot interferometer (Yariv, 1985; Kashima, 1995), which is shown in Fig. 3. In Fig. 3 (a), a flat board with thickness S and refractive index n is placed in a medium with refractive index n_1. Figure 3 (b) shows a fiber connection with a small gap. Here, small means a length of wavelength order. The incident light I_i, transmitted light I_t, and returned light I_r in both figures is considered to behave identically. In Fig. 3 (b), Fresnel reflections occur at the fiber ends because of refractive discontinuity, and some of the incident light is multiply reflected in the small gap. As the phase of the multiply reflected light changes whenever it is reflected, this interferes with the transmitted and reflected lights at the small gap. These multiple reflections between fiber ends are considered to behave like a Fabry-Perot interferometer. The two fiber ends make up the Fabry-Perot resonator. On the basis of the analysis, the reflection coefficient R of optical fiber connections with a gap is defined by the following equations.
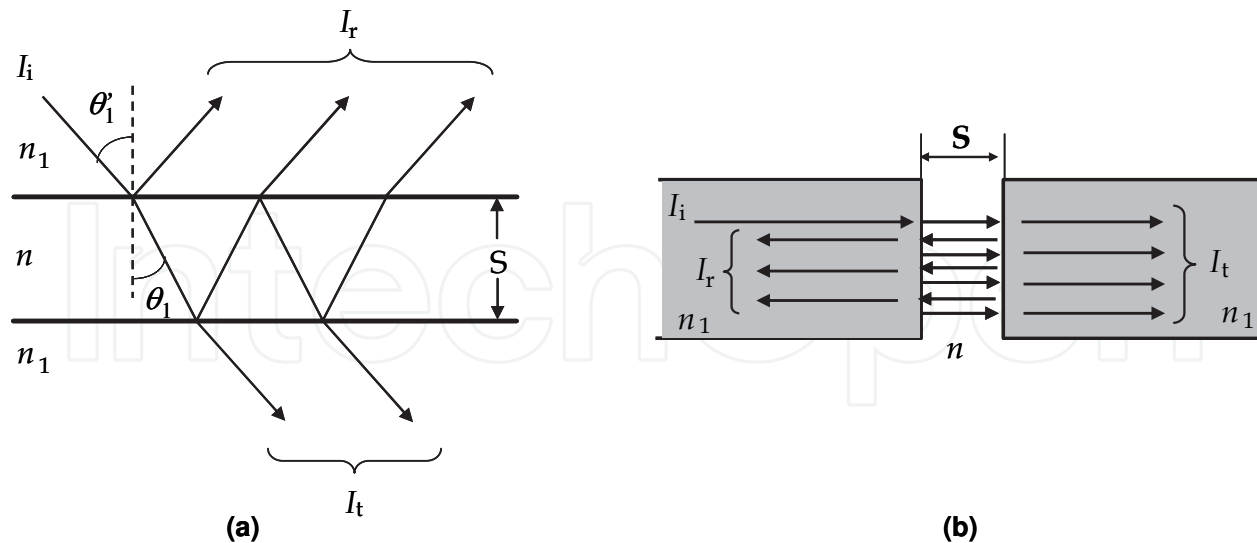
Fig. 3. (a) Fabry-Perot interference model, (b) model of fiber connection with small gap.

$$R = \frac{I_r}{I_i} = \frac{4R_0 \sin^2(\delta/2)}{(1-R_0)^2 + 4R_0 \sin^2(\delta/2)} \tag{6}$$

$$\delta = \frac{4\pi n S \cos\theta_1}{\lambda}$$

Here, δ, n, S, and R_0 are the phase difference, refractive index of the medium, gap size between fiber ends, and reflection coefficient at the fiber core and the medium (Eq. (5)), respectively. If $R_0 \ll 1$, Eq. (6) can be transformed to the following equation.

$$R = 2R_0(1 - \cos\delta) \tag{7}$$

When the fiber ends for the connection are flat, smooth, and perpendicular to the fiber axis, the incident angle θ_1' and the angle θ_1 can be 0 rad. Therefore, Eq. (7) can be transformed to the following equation.

$$R = 2R_0\left(1 - \cos\left(\left(\frac{4\pi n}{\lambda}\right)S\right)\right) \tag{8}$$

This equation is generally used to analyze the return loss of a SMF connection. If more detailed analyses on return loss, such as for polished fiber end connections (a fiber connection whose ends have a high-refractive-index layer) are needed, the work by Young (1991) and Kihara et al. (1996) is recommended.

3. Air-filled gap

This section reveals the performance of fiber connections with air-filled gaps. This case might occur when a fiber connection using PC experiences an unexpected failure, resulting in imperfect PC.

3.1 Wavelength dependence

We focus our investigation on the characteristics of optical fiber connections caused by the gap between the fiber ends. Misalignments of the offset and tilt between the fibers, and the mode field mismatch are not considered. Analysis of optical performance affected by a small gap between fiber ends is based on multiple reflections behaving like a Fabry-Perot interferometer. Here, a small gap means a length of wavelength order. On the basis of the analysis, the transmission coefficient T and the reflection coefficient R of optical fiber connections with an air-filled gap are defined by the following equations.

$$T = \frac{(1 - R_0)^2}{(1 - R_0)^2 + 4R_0 \sin^2(2\pi nS / \lambda)} \tag{9}$$

$$R = \frac{4R_0 \sin^2(2\pi nS / \lambda)}{(1 - R_0)^2 + 4R_0 \sin^2(2\pi nS / \lambda)} \tag{10}$$

The insertion and return losses in dB are derived by multiplying -10 by the log of the transmission and reflection coefficient functions. Here, n_1, n, S, and λ are the refractive indices of the fiber core and of air, and the gap size and wavelength, respectively. R_0 is the reflection coefficient defined by Eq. (5). According to Eqs. (9) and (10), the insertion and return losses depend on wavelength λ and gap size S. The wavelength dependence of the insertion and return losses over a wide wavelength range was experimentally investigated by using mechanically transferable (MT) connectors (Satake et al., 1986). MT connectors without refractive-index matching material generally have small air-filled gaps between their fiber ends (Kihara et al., 2006). The insertion and return losses of MT connectors with an air-filled gap were measured over a wide wavelength range using halogen-lamp or supercontinuum light sources, an optical spectral analyzer, and an optical coupler. The supercontinuum light source can output over +20 dBm/nm more power than the halogen-lamp light source. Two sets of results for MT connectors with air-filled gaps are shown in Figs. 4 (a) and (b), respectively. The circles and lines represent the measured results and the calculations based on Eqs. (9) and (10), respectively. The refractive indices n_1 and n were 1.454 and 1.0, and the gap size S for calculations was 1.13 μm in (a) and 1.3 μm in (b). The calculated and measured data for insertion loss varied between 0.0 and 0.6 dB over a wide wavelength range. The data for return loss varied greatly and resulted in a worst value of 8.7 dB. These two sets of measured results are in good agreement with the calculations. They showed that the insertion and return losses for fiber connections with small air-filled gaps vary greatly and periodically depending on wavelength.

3.2 Gap size dependence

The gap size dependence of the optical performance of fiber connections with an air-filled gap was also investigated. If the gap size between fiber ends is small, the performance could be determined based on the analysis in section 3.1. However, if the gap is larger than a length of wavelength order, radiation loss could occur in it. The attenuation ratio A is defined using the Marcuse equation (1) in terms of the gap between the fiber ends as follows:

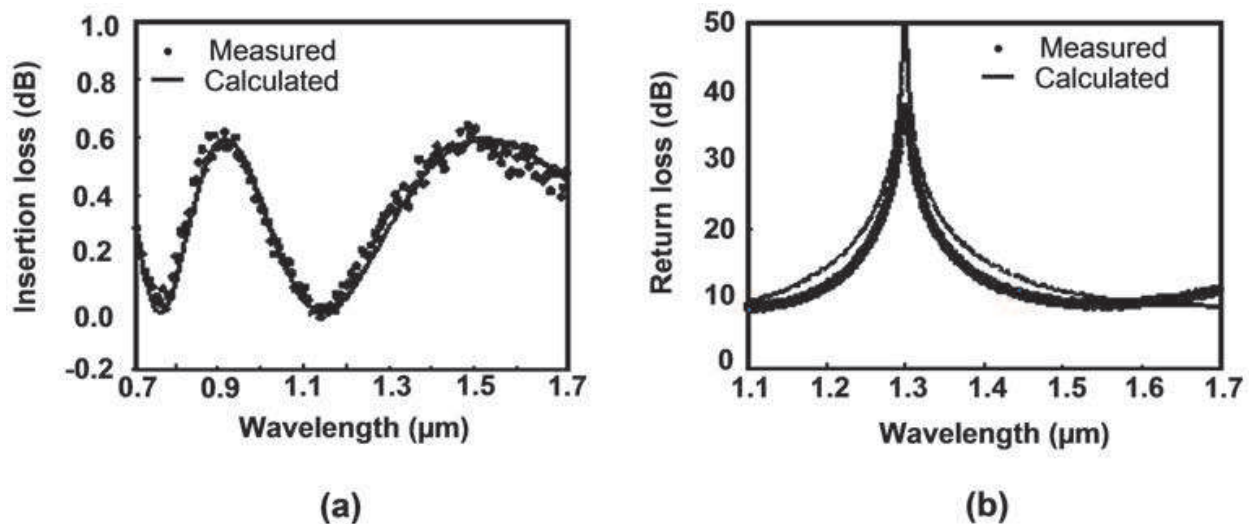$$A = \left[\left(\frac{\lambda S}{2\pi n \omega^2} \right)^2 + 1 \right]^{-1} \tag{11}$$

Fig. 4. Wavelength dependence of fiber connections with air-filled gap. (a) Insertion loss results, (b) return loss results.

Here, ω is the mode field radius of the transmitted light. Considering the attenuation in the gap between fiber ends, the transmission coefficient T and the reflection coefficient R are derived from Eqs. (9) and (10) as

$$T = \frac{A(1-R_0)^2}{(1-AR_0)^2 + 4AR_0 \sin^2(2\pi nS/\lambda)} \tag{12}$$

$$R = \frac{[\{1+A(1-2R_0)\}^2 - 4A(1-2R_0)\sin^2(2\pi nS/\lambda)]R_0}{(1-AR_0)^2 + 4AR_0 \sin^2(2\pi nS/\lambda)} \tag{13}$$

T and R are dependent on gap size S according to Eqs. (12) and (13), which are more complicated than Eqs. (9) and (10), respectively. To demonstrate these dependences, another experiment using an MT connector was performed (Kihara et al., 2010). A feeler gauge (thickness gauge tape) was set and fixed between the two MT ferrules of a connector with a certain gap size by using a clamp spring. By changing the thickness of the feeler gauge, various sizes of gaps were obtained. An air-filled gap was obtained without using refractive-index matching material. The insertion and return losses for the fiber connections with various air-filled gap sizes are shown in Figs. 5(a) and (b), respectively. The circles and lines represent the measured results and the calculations based on Eqs. (12) and (13), respectively. The refractive indices n_1 and n were 1.454 and 1.0, and the wavelength λ for calculations was 1.31 μm in both (a) and (b). The calculated values for insertion and return losses oscillated. This oscillation is caused by the multiple reflection interference in an air-filled gap, which was described earlier. The range of oscillation changed with the gap size. When the gap size was as small as a length of wavelength order, the range of oscillation was large. When the gap size was much larger, the range of oscillation was smaller. This suggests that the insertion and return losses when the gap is small mainly depend on the multiple reflection interference, and that those when the gap is much larger are affected by the radiation loss in an air-filled gap. The measured insertion loss increased with the gap
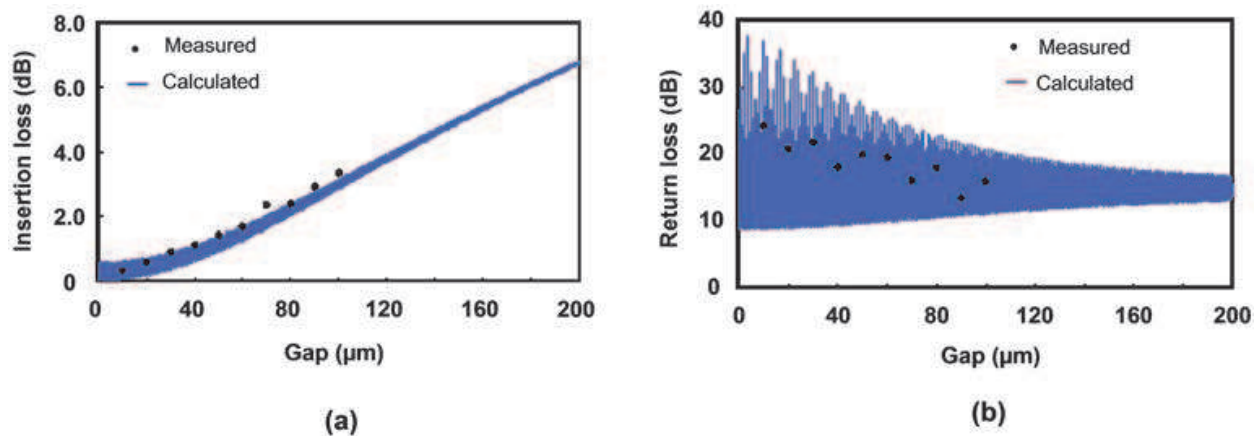
Fig. 5. Gap-size dependence of fiber connections with air-filled gap. (a) Insertion loss results, (b) return loss results.

size as well as the calculated values. The measured return loss varied greatly, but the values were within the oscillation range of the calculated results. The calculated return loss when the gap was much larger was close to 14.7 dB, which is a value of Fresnel reflection at a cleaved fiber end in air. These two sets of measured results are in good agreement with the calculations. Consequently, we theoretically and experimentally revealed the optical performance of fiber connections with various air-filled gap sizes.

3.3 Optical performance of fiber connections with imperfect physical contact

The optical-performance deterioration of a PC-type connector with an imperfect physical contact, i.e., when an air gap occurs unexpectedly at the contact point was also investigated. The experiments using a single-fiber coupling optical fiber (SC) connector (Sugita et al., 1989) were performed. An SC connector is a push-on-type connector and is composed of two plugs and an adaptor. The plug and adaptor are engaged by fitting a pair of elastic hooks into corresponding grooves. Failure to connect the mated connector, such as an incorrect hooking or an existing contamination on a connector end surface, leads to imperfect physical contact and the occurrence of an air-filled gap at the contact point of the connector. An incorrect hooking was intentionally created and 140 SC connector fault samples that had imperfect physical contact were fabricated as investigation samples. The insertion and return losses at a wavelength of 1.3 µm of the fabricated SC connector fault samples are shown in Figs. 6 (a) and (b). The insertion and return losses for SC connectors that maintain physical contact generally are under 0.5 dB and over 40 dB, respectively. In contrast, for the SC connector fault samples with imperfect physical contact, the minimum, maximum, and mean insertion losses were 0.0, 18.1, and 8.7 dB, respectively. The return loss varied between 9.4 and 23.1 dB, and the mean value was 14.6 dB. The results revealed that the optical performance of fiber connections with imperfect physical contact could deteriorate greatly.

Consequently, the optical performances of fiber connections with an air-filled gap are extremely unstable and vary widely. At worst, the insertion and return losses might deteriorate to ~18 and 9.4 dB, respectively. Therefore, air-filled gaps between fiber ends must be prevented from occurring in PC-type connectors.
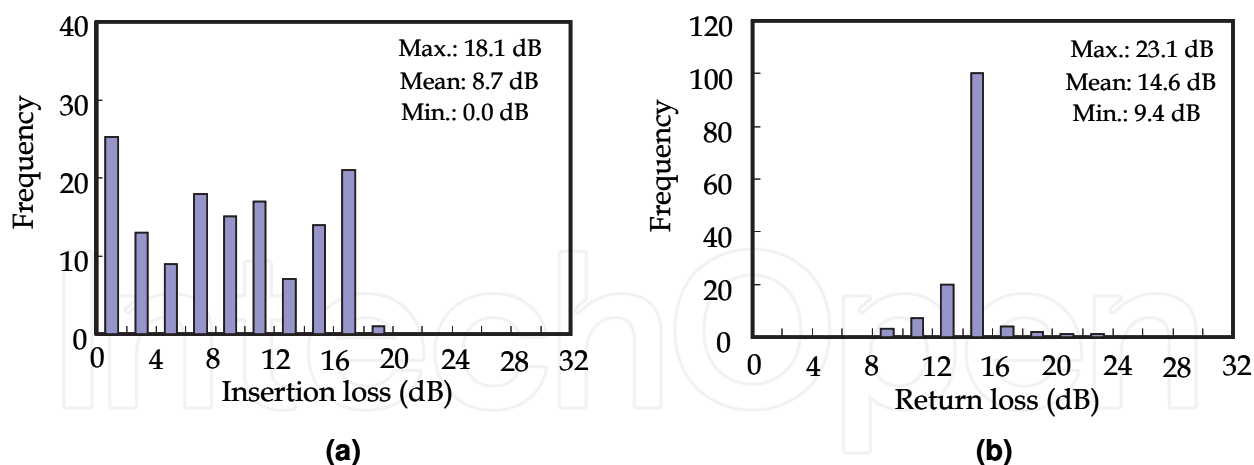
(a)   **(b)**

Fig. 6. Optical performance of SC connector fault samples with air-filled gap. (a) Insertion loss results, (b) return loss results.

4. Mixture of refractive-index matching material and air-filled gaps

This section reports a loss analysis for fiber connections with a mixture of refractive-index matching material and air-filled gaps. This case might occur when an optical connector or a mechanical splice using refractive-index matching material experiences an unexpected failure.

4.1 Optical fiber connection with gap

We first focus our investigation on the insertion loss of optical fiber connections caused by the gap between fiber ends. The misalignments of the offset and tilt between the fibers and the mode field mismatch were not taken into account.

There are two analysis techniques for insertion losses caused by these gaps. One is based on multiple reflection analyses, such as that using a Fabry-Perot interferometer, when the gap is small (i.e., of wavelength order). This is expressed by Eq. (9). The other is the Marcuse analysis, which is used when the gap is much longer than the wavelength. This is expressed by Eq. (1). The typical insertion loss results for fiber connections with a small air-filled gap and with refractive-index matching material between the fiber ends are shown in Fig. 7(a). The insertion loss results for fiber connections with long gaps are shown in Fig. 7(b). The measured data were obtained using MT connectors such as described in the previous section. Silicone oil was used as the refractive-index matching material. The circles and squares represent measured results obtained with air-filled and refractive-index matching-material-filled gaps, respectively. The solid and dashed lines indicate the respective calculated results using the above equations. When the gap is small, insertion losses for the air-filled gap vary between 0.0 and 0.6 dB over a wide wavelength range, as shown in Fig. 7 (a). In contrast, the losses for the refractive-index matching-material-filled gap are negligible. According to the multiple reflection analysis, the losses vary between 0.0 and 0.6 dB depending on the gap length if the wavelength is constant. In contrast, when the gap is much longer than the wavelength, the insertion loss worsens and becomes much larger, as shown in Fig. 7 (b). The loss increases with gap length. For instance, the insertion loss for an air-filled gap increases to ~0.8 dB when the gap is 50 μm. These two sets of results are in
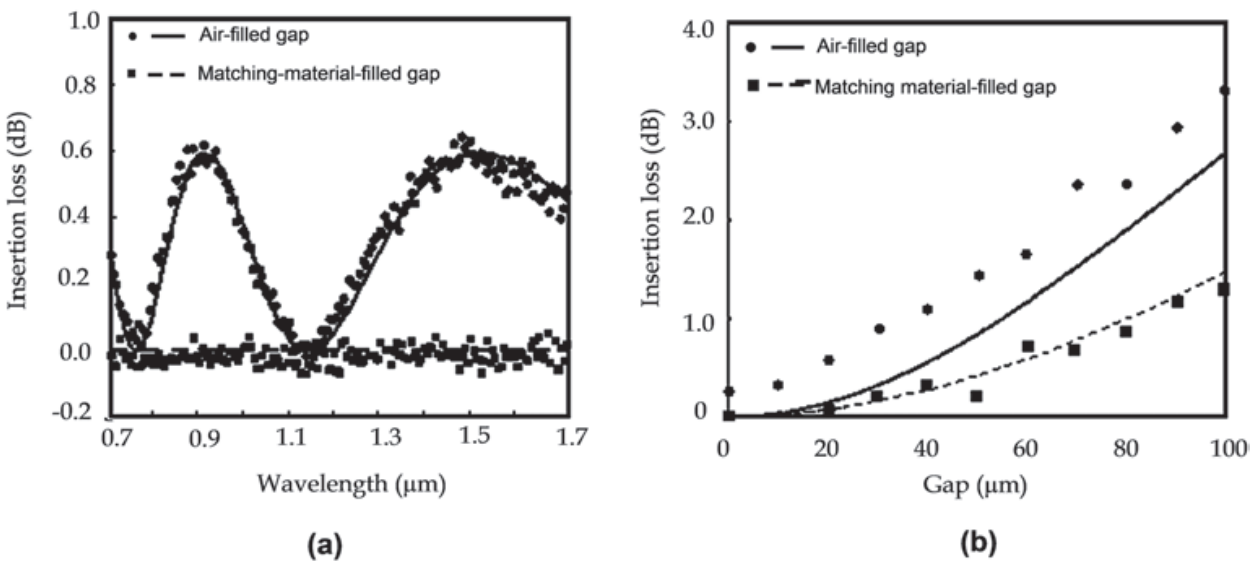
Fig. 7. Optical performance of fiber connections with various gaps. (a) Small gap: 1.1 μm over wide wavelength range of 0.7–1.7 μm. (b) Large gaps: 10 to 100 μm at wavelength of 1.3 μm.

good agreement with the calculations based on the multiple reflection and Marcuse analyses. This indicates that an experiment using feeler gauges is effective for analyzing fiber connections with various gaps.

S. Yoshino et al. reported the results of a mechanical splice fault (Yoshino et al., 2008). The maximum insertion loss change of the mechanical splice with a large gap of less than 50 μm was more than 10 dB during a heat-cycle test. This loss is much larger than the values obtained by the above two analyses. Thus the factors leading to the difference between these results and the conventional theory were experimentally investigated.

4.2 Mixture of refractive-index matching material and air-filled gaps

This section describes the experimental results for fiber connections with a mixture of refractive-index matching material and air-filled gaps. The following experiments using MT connectors with a feeler gauge were performed (Kihara et al., 2009) . MT ferrules without using a feeler gauge (conventionally) were first connected, where refractive-index matching material was used between the ferrule ends. Next, one ferrule pair was disconnected and only one of the ferrule ends was cleaned with alcohol. Then, the cleaned ferrule and the ferrule with refractive-index matching material were connected to a 50-μm feeler gauge. A schematic and photographs of the connected MT ferrules are shown in Fig. 8, and the insertion and return losses of the four fibers in the MT connector are listed in Table 1. The direction of light input to the MT connector changed. The results of the two directions, **a** and **b**, are also listed. Every return loss in the same direction was almost equal. The return loss values in the two directions indicated that a mixture of refractive-index matching material and air-filled gaps existed between the fiber ends. In contrast, there was little difference between the insertion losses for different directions within the same fiber, but the insertion loss of each of the four fibers was different. The lowest insertion loss was 3 dB, and the highest was about 40 dB. These results reveal that the insertion loss of fiber connections with a mixture of matching material and air-filled gaps might increase to more than 10 dB.
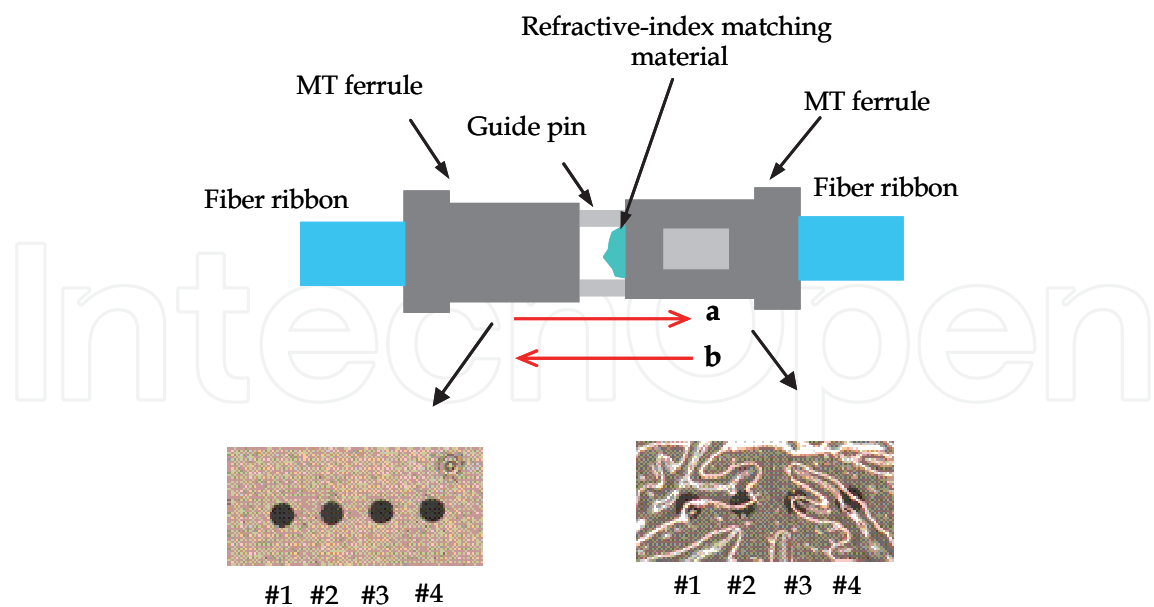
Fig. 8. Schematic view and photographs of MT ferrule samples with mixture of refractive-index matching material and air-filled gaps (50 µm).

Direction *a*					Direction *b*				
Fiber number	#1	#2	#3	#4	Fiber number	#1	#2	#3	#4
Insertion loss (dB)	3.2	9.8	20.4	41.7	Insertion loss (dB)	3.1	9.8	21.8	39.5
Return loss (dB)	15.8	16.0	15.9	16.7	Return loss (dB)	24.5	46.2	40.2	47.3

Table 1. Insertion and return loss results.

Another experiment with various gaps: an air-filled gap, a refractive-index matching-material-filled gap, and a mixture of refractive-index matching material and air-filled gaps was conducted. The procedure for creating connections with a mixture of refractive-index matching material and air-filled gaps was described above. The results are shown in Fig. 9. All data are results for a gap of 50 µm. We used 20 individual fiber samples. For fiber connections with air-filled gaps, the minimum, maximum, and mean insertion losses were 0.8, 4.0, and 1.2 dB, respectively. The return losses varied between 15 and 26 dB. With refractive-index matching-material-filled gaps, the insertion losses were less than 0.4 dB, the mean value was 0.25 dB, and the return losses were more than 50 dB. With a mixture of refractive-index matching material and air-filled gaps, the insertion losses on one side attachment were from 1.1 to 42 dB (mean value of 12.0 dB) and the return losses varied between 13 and 47 dB. The insertion losses on the other side attachment were from 0.7 to 35 dB (mean value of 11.3 dB), and the return losses varied between 13 and 18 dB. These results indicate that the insertion and return losses with a mixture of refractive-index matching material and air-filled gaps vary greatly and are unstable.

An MT connector sample with a 50-µm gap containing a mixture of refractive-index matching material and air was made. Then a heat-cycle test in accordance with IEC 61300-2-22 (-40 to 70°C, 10 cycles, 6 h/cycle) on the sample was performed. The insertion and return losses of the sample are shown in Fig. 10. The optical performances changed and were
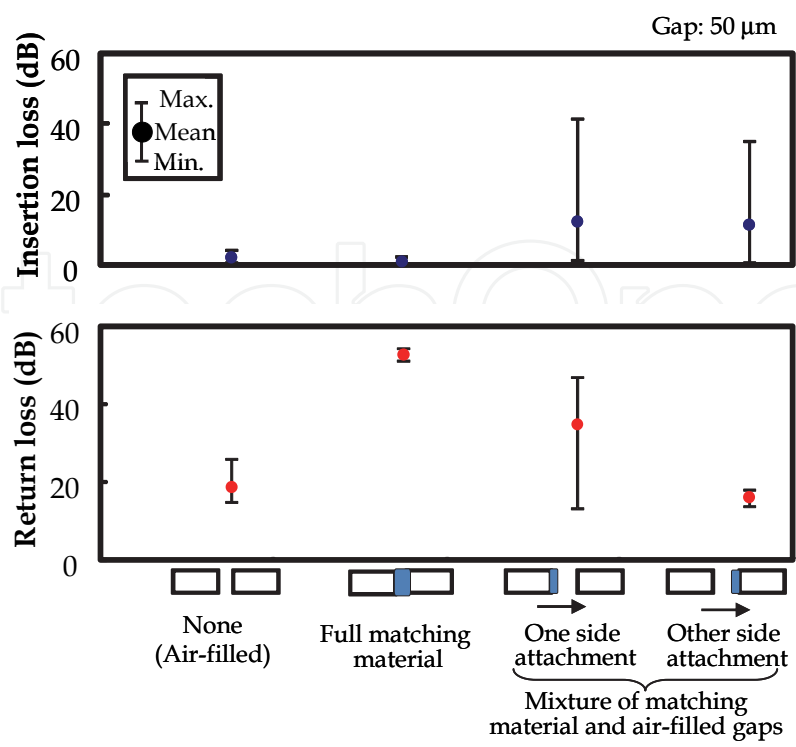
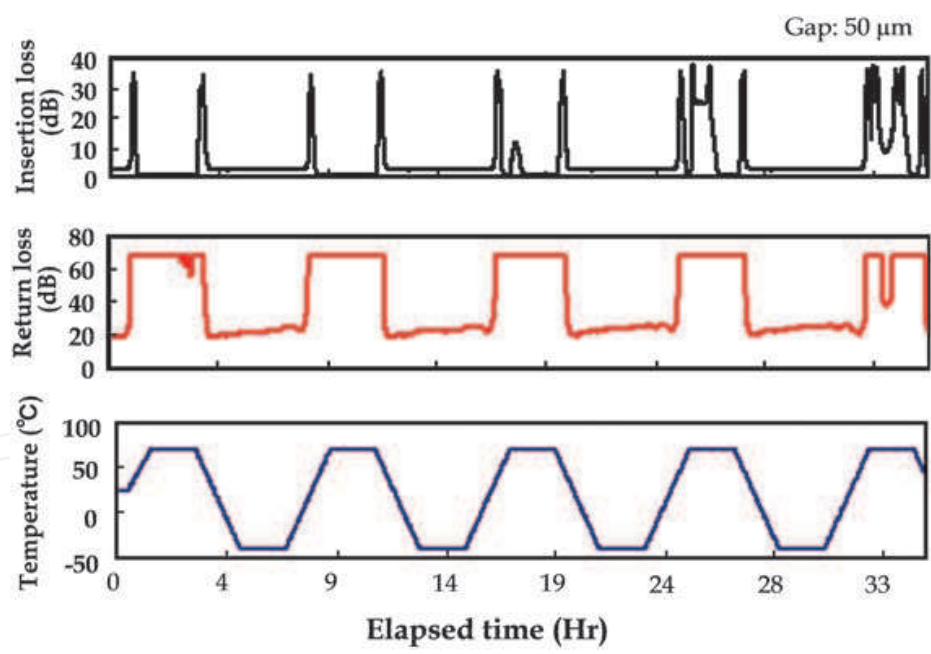Fig. 9. Relation between gap states of fiber connections and optical performance.

Fig. 10. Heat-cycle test results for fiber connection with mixture of refractive-index matching material and air-filled gaps.

unstable. The insertion loss was initially 2.7 dB and then varied when the temperature changed. The maximum insertion loss was more than 30 dB. The return losses also varied from 20 dB to more than 60 dB. This performance deterioration is thought to be caused by the mixture of refractive-index matching material and air-filled gaps between the fiber ends in the MT connector sample. Refractive-index matching material moved in the gap when the

temperature changed, and the mixed-state change of the refractive-index matching material and the air between the fiber ends resulted in the change in optical performance. In a mixed state of refractive-index matching material and air between fiber ends, the boundary between the refractive-index matching material and air could be uneven. In this state, the transmitted light spread randomly in every direction at the boundary, which is similar to an incorrectly cleaved fiber end (uneven end perpendicular to the fiber axis). Therefore, the insertion loss increased to more than 30 dB.

Consequently, the optical performances of fiber connections with a mixture of refractive-index matching material and air-filled gaps are extremely unstable and vary widely. At worst, the insertion loss is more than 30 dB because the light spreads in every direction in the gap between fiber ends. Therefore, it is important to prevent the gap from becoming larger and avoid mixing air into the refractive-index matching material in the gap between fiber ends for these fiber connections.

5. Unexpected use of incorrectly cleaved fiber ends

In this section, the performance deterioration of fiber connections using an incorrectly cleaved fiber end is discussed. This case might occur when a field-assembly connector or a mechanical splice experiences an unexpected failure.

5.1 Incorrectly cleaved fiber end and fiber connection

An incorrectly cleaved fiber end is caused by problems with the fiber cleaver, such as a dropped cleaver or one that has struck something, because a fiber cleaver is a precisely fabricated and sensitive tool. If there are no problems with the fiber cleaver, the fiber will be cleaved correctly and have an ideal flat and smooth end perpendicular to the fiber axis. However, if there are problems, the fiber will be cleaved incorrectly and have an uneven end (NTT East, 2011). The mechanism of correctly and incorrectly cleaving fiber ends is shown in Fig. 11. The procedure of cleaving optical fibers is as follows. A scratch (origin of fracture) is first made on the fiber by the blade of the cleaver. The fiber is then bent at the origin of fracture at an appropriate radius and pushed from the opposite side of the origin of fracture until the fiber is eventually cleaved. Incorrectly cleaved fiber ends are reported to result from an incorrect bend radius during cleaving (Glode et al., 1973; Haibara et al., 1986). If the bend radius is too small, the cleaved fiber end will have a lip. If the bend radius is too large, the cleaved fiber end will have a hackle. A cleaved fiber end with a lip or hackle is not flat or smooth. Therefore, it is important for fiber cleavers to maintain the correct radius when bending fibers.

The normal connection state of correctly cleaved fiber ends and the abnormal state of an incorrectly cleaved fiber ends are shown in Fig. 12. The normal connection state (Fig. 12(a)) has a very small gap between the correctly cleaved fiber ends, and the gap is filled with refractive-index matching material (matching material). The abnormal connection state (Fig. 12(b)) has a large gap between the correctly cleaved (flat) fiber end and incorrectly cleaved (uneven with a lip) fiber end. The gap is filled with refractive-index matching material, but it is so large that it may affect the optical performance. This may be similar to the performance deterioration caused by a large gap between flat fiber ends (Kihara et al., 2009).
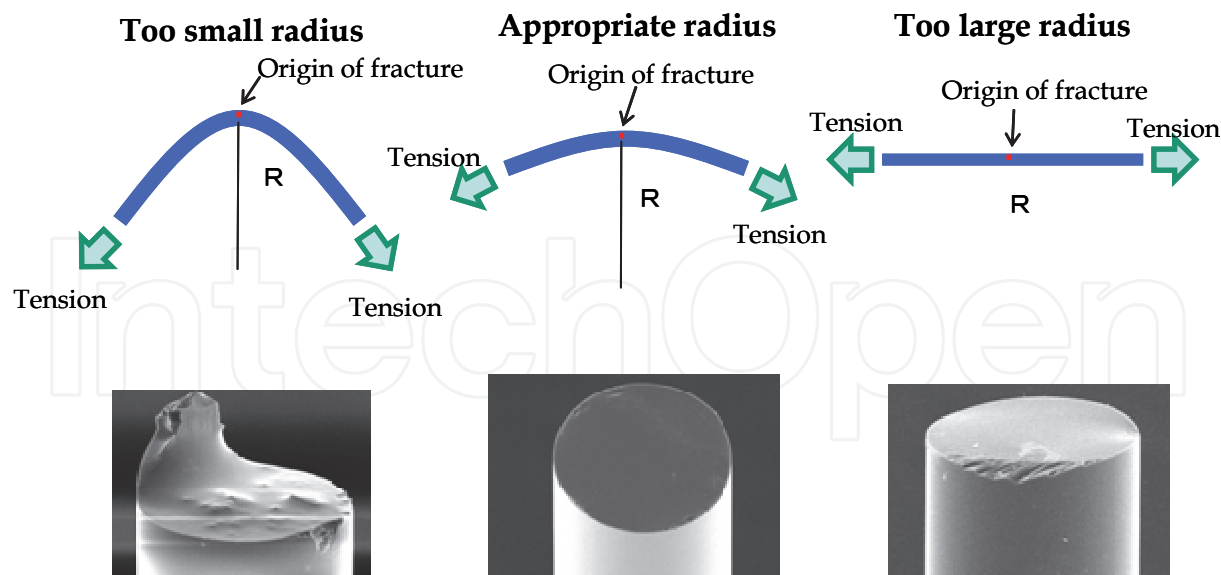
Too small radius   **Appropriate radius**   **Too large radius**

Fig. 11. Mechanism of correctly and incorrectly cleaving fiber ends.

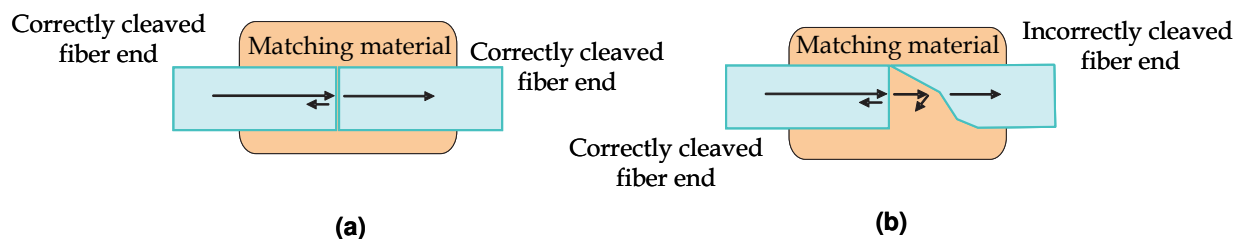**(a)**   **(b)**

Fig. 12. Fiber connection states using correctly and incorrectly cleaved fiber ends.

5.2 Experiments and results

The optical performances of fiber connections using an incorrectly cleaved fiber end were experimentally investigated (Yajima et al., 2011). As investigation samples, 25 field assembly connectors using incorrectly cleaved fiber ends were fabricated. These incorrectly cleaved fiber ends were intentionally made by adjusting the fiber cleaver so that the bend radius would be too small. The cracks of these incorrectly cleaved fiber ends were from 30 to 200 μm in the axial direction. Five connectors using correctly cleaved flat fiber ends were also made for comparison. All 30 connectors were subjected to a heat-cycle test in accordance with IEC 61300-2-22 (-40 to 70°C, 10 cycles, 6 h/cycle) to simulate conditions in the field. We measured the insertion and return losses at a 1.55-μm wavelength.

The results for a sample using correctly cleaved fiber ends (sample 1) are shown in Fig. 13. The initial insertion loss was less than 0.5 dB, and the maximum insertion loss during the test was less than 0.8 dB. The return loss varied from 46 to 62 dB. This variance is thought to have been caused by a tiny refractive-index change in the matching material along with the change in temperature (Kihara et al., 1995). The insertion losses were very low and the return losses were very high. The performance was very stable.

The results for two samples fabricated using incorrectly cleaved fiber ends varied greatly (Figs. 14(a) and (b)). The insertion loss of sample 2 (Fig. 14(a)) varied from 0.4 to 0.9 dB. This variance is thought to have been caused by a tiny offset or tilt between the fiber ends. The
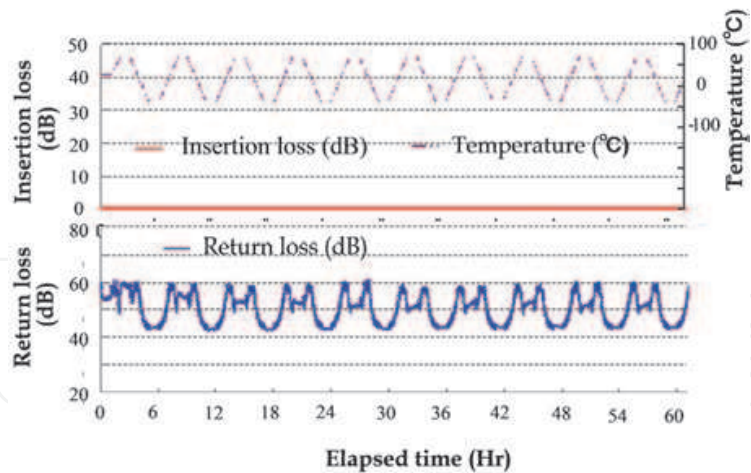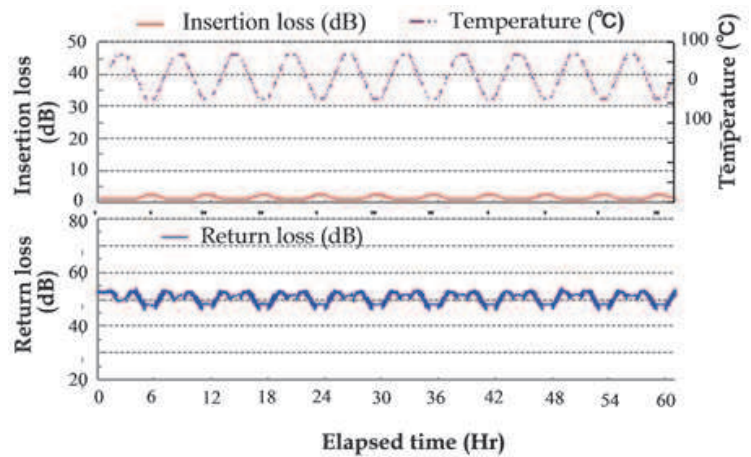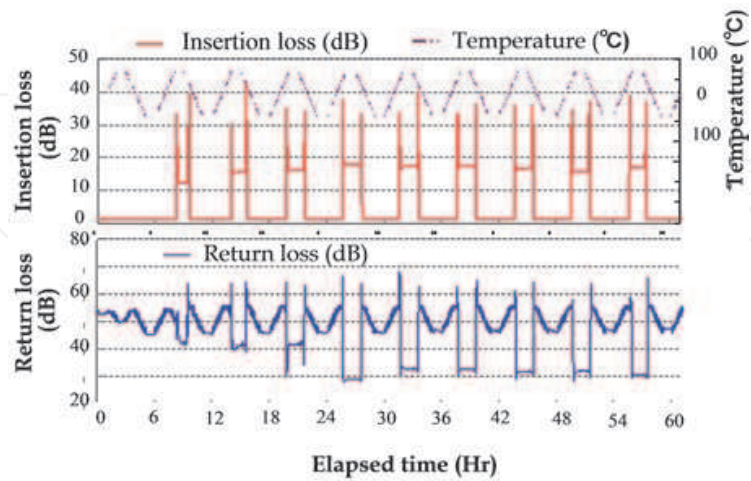
Fig. 13. Heat-cycle test result for connector using correctly cleaved fiber ends (sample 1).

(a)

(b)

Fig. 14. Heat-cycle test results for connectors using incorrectly cleaved fiber ends. (a) Sample 2, (b) sample 3.

return loss was always over 40 dB. This performance is very stable and almost the same as that of correctly cleaved fiber ends (sample 1). The initial insertion loss of sample 3 (Fig. 14(b)) was 1.0 dB. The insertion loss of this sample changed from about 1.0 dB to more than 40 dB, according to the change in temperature. The return loss was temporally less than 30 dB. The change of the insertion and return losses is attributed to the partially air-filled gap. The gap was not completely filled with matching material; it was partially filled with air because of the incorrectly cleaved fiber end. The return loss in sample 3 is considered to be smaller than that in sample 2 due to this air gap. These results suggest that the insertion and return losses of fiber connections using incorrectly cleaved fiber ends might change to, at worst, more than 40 dB and less than 30 dB, respectively. This performance is very unstable. Such a substantial increase in insertion loss can affect the quality of an optical network service. Therefore, incorrectly cleaved fiber ends must not be used. A countermeasure is to inspect the cleaved fiber end before installing fiber connections such as a mechanical splice or a field assembly connector (Kihara et al., 2011; Okada et al., 2011).

Overall, the optical performances of fiber connections using an incorrectly cleaved fiber end vary widely. At worst, the insertion and return losses might deteriorate to more than 40 dB and less than 30 dB, respectively.

6. Conclusion

The performances of SMF connections were experimentally investigated for various cases: connections with (1) air-filled gaps, (2) a mixture of refractive-index matching material and air-filled gaps, and (3) unexpected use of an incorrectly cleaved fiber end. The cases were assumed to occur accidentally as the result of unexpected failure during and after installation of fiber connections in the field. In this chapter, the optical performance deterioration of these fiber connections was detailed.

After a brief introduction (section 1), the conventional loss characteristics of SMF connections based on the D. Marcuse and W. C. Young analyses were explained in section 2. From section 3 onward, the insertion and return losses of the fiber connections were reported.

In section 3, the performance of fiber connections with air-filled gaps was explained. This case might occur when a fiber connection using PC experiences an unexpected failure. Generally, the optical performance of a connector that maintains perfect PC will remain environmentally stable. However, when there is an air-filled gap between fiber ends with PC-type connections, the optical performance worsens noticeably. In particular, the return loss varies greatly and might deteriorate to 8.7 dB for one fiber connection at worst.

In section 4, a loss analysis for fiber connections with a mixture of refractive-index matching material and air-filled gaps was reported. This case might occur when an optical connector or a mechanical splice using refractive-index matching material experiences an unexpected failure. The connections normally have a small gap between the fiber ends, and the gap is filled with refractive-index matching material to reduce Fresnel reflection; the optical performance will remain environmentally stable. However, when there is a large gap between fiber ends and the connections use refractive-index matching material, the gap might change to a mixture of refractive-index matching material and air-filled gaps. The

optical performance worsens noticeably in this case. In particular, the insertion loss varies greatly and might deteriorate by more than 30 dB for one fiber connection.

In section 5, the performance deterioration of fiber connections using an incorrectly cleaved fiber end was shown. This case might occur when a field-assembly connector or a mechanical splice experiences an unexpected failure. For these fiber connections, it is necessary to strip the fiber coating, clean the stripped fiber with alcohol, and cut the fiber with a cleaver while in the field. If the optical fiber of the connection is not cut correctly, the insertion loss of the fiber connection might deteriorate by more than 30 dB in the same way as that for a fiber connection with a mixture of refractive-index matching material and air-filled gaps.

This chapter discussed the characteristics based on the results obtained for MT, SC, and field assembly connectors. However, the results can be applied to other connectors or fiber connections. These results are considered to be useful for practical construction and operation of optical fiber network systems.

7. Acknowledgments

8. References

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